

Planck intermediate results. XLVII.

Planck constraints on reionization history

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ABSTRACT

We investigate constraints on cosmic reionization extracted from the *Planck* cosmic microwave background (CMB) data. We combine the *Planck* CMB anisotropy data in temperature with the low-multipole polarization data to fit Λ CDM models with various parameterizations of the reionization history. We obtain a Thomson optical depth $\tau = 0.058 \pm 0.012$ for the commonly adopted instantaneous reionization model. This confirms, with data solely from CMB anisotropies, the low value suggested by combining *Planck* 2015 results with other data sets, and also reduces the uncertainties. We reconstruct the history of the ionization fraction using either a symmetric or an asymmetric model for the transition between the neutral and ionized phases. To determine better constraints on the duration of the reionization process, we also make use of measurements of the amplitude of the kinetic Sunyaev-Zeldovich (kSZ) effect using additional information from the high-resolution Atacama Cosmology Telescope and South Pole Telescope experiments. The average redshift at which reionization occurs is found to lie between $z = 7.8$ and 8.8 , depending on the model of reionization adopted. Using kSZ constraints and a redshift-symmetric reionization model, we find an upper limit to the width of the reionization period of $\Delta z < 2.8$. In all cases, we find that the Universe is ionized at less than the 10 % level at redshifts above $z \approx 10$. This suggests that an early onset of reionization is strongly disfavoured by the *Planck* data. We show that this result also reduces the tension between CMB-based analyses and constraints from other astrophysical sources.

Key words. Cosmology – cosmic background radiation – Polarization – dark ages, reionization, first stars

1. Introduction

The process of cosmological recombination happened around redshift $z \approx 1100$, after which the ionized fraction fell precipitously (Peebles 1968; Zel'dovich et al. 1969; Seager et al. 2000) and the Universe became mostly neutral. However, observations of the Gunn-Peterson effect (Gunn & Peterson 1965) in quasar spectra (Becker et al. 2001; Fan et al. 2006b; Venemans et al. 2013; Becker et al. 2015) indicate that intergalactic gas had become almost fully reionized by redshift $z \approx 6$. Reionization is

thus the second major change in the ionization state of hydrogen in the Universe. Details of the transition from the neutral to ionized Universe are still the subject of intense investigations (for a recent review, see the book by Mesinger 2016). In the currently conventional picture, early galaxies reionize hydrogen progressively throughout the entire Universe between $z \approx 12$ and $z \approx 6$, while quasars take over to reionize helium from $z \approx 6$ to $z \approx 2$. But many questions remain. When did the epoch of reionization (EoR) start, and how long did it last? Are early galaxies enough to reionize the entire Universe or is another source required? We try to shed light on these questions using the traces left by the EoR in the cosmic microwave background (CMB) anisotropies.

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The CMB is affected by the total column density of free electrons along each line of sight, parameterized by its Thomson scattering optical depth τ . This is one of the six parameters of the baseline Λ CDM cosmological model and is the key measurement for constraining reionization. Large-scale anisotropies in polarization are particularly sensitive to the value of τ . The WMAP mission was the first to extract a τ measurement through the correlation between the temperature field and the E -mode polarization (i.e., the TE power spectrum) over a large fraction of the sky. This measurement is very demanding, since the expected level of the E -mode polarization power spectrum at low multipoles ($\ell < 10$) is only a few times $10^{-2} \mu\text{K}^2$, lower by more than two orders of magnitude than the level of the temperature anisotropy power spectrum. For such weak signals the difficulty is not only to have enough detector sensitivity, but also to reduce and control both instrumental systematic effects and foreground residuals to a very low level. This difficulty is illustrated by the improvements over time in the WMAP-derived τ estimates. The 1-year results gave a value of $\tau = 0.17 \pm 0.04$, based on the temperature-polarization TE cross-power spectrum (Kogut et al. 2003). In the 3-year release, this was revised down to 0.10 ± 0.03 using E -modes alone, whereas the combined TT , TE , and EE power spectra gave 0.09 ± 0.03 (Page et al. 2007). Error bars improved in further WMAP analyses, ending up with 0.089 ± 0.014 after the 9-year release (see Dunkley et al. 2009; Komatsu et al. 2011; Hinshaw et al. 2013). In 2013, the first *Planck* satellite¹ cosmological results were based on *Planck* temperature power spectra combined with the polarized WMAP data and gave the same value $\tau = 0.089 \pm 0.014$ (Planck Collaboration XVI 2014). However, using a preliminary version of the *Planck* 353 GHz polarization maps to clean the dust emission (in place of the WMAP dust model), the optical depth was reduced by approximately 1σ to $\tau = 0.075 \pm 0.013$ (Planck Collaboration XV 2014).

In the 2015 *Planck* analysis (Planck Collaboration XIII 2016), the Low Frequency Instrument (LFI) low-resolution maps polarization at 70 GHz were used. Foreground cleaning was performed using the LFI 30 GHz and High Frequency Instrument (HFI) 353 GHz maps, operating effectively as polarized synchrotron and dust templates, respectively. The optical depth was found to be $\tau = 0.078 \pm 0.019$, and this decreased to 0.066 ± 0.016 when adding CMB lensing data. This value is also in agreement with the constraints from the combination “PlanckTT+lensing+BAO,” yielding $\tau = 0.067 \pm 0.016$, which uses no information from low- ℓ polarization.

In this paper and its companion (Planck Collaboration Int. XLVI 2016), we derive the first estimate of τ from the *Planck*-HFI polarization data at large scales. For the astrophysical interpretation, the power spectra are estimated using a PCL estimate which is more conservative. Indeed, it gives a slightly larger distribution on τ than the QML estimator used in Planck Collaboration Int. XLVI (2016) but is less sensitive to the limited number of simulations available for the analysis. Using only E -mode polarization, the *Planck* lollipop likelihood gives $\tau = 0.053^{+0.014}_{-0.016}$ for a standard instantaneous reionization model, when all other Λ CDM parameters are fixed to their *Planck*-2015 best-fit values. We show that in

combination with the *Planck* temperature data the error bars are improved and we find $\tau = 0.058 \pm 0.012$.

In the Λ CDM model, improved accuracy on the reionization optical depth helps to reduce the degeneracies with other parameters. In particular, the measurement of τ reduces the correlation with the normalization of the initial power spectrum A_s and its spectral index n_s . In addition to this τ is a particularly important source of information for constraining the history of reionization, which is the main subject of this paper. When combined with direct probes at low redshift, a better knowledge of the value of the CMB optical depth parameter may help to characterize the duration of the EoR, and thus tell us when it started.

In addition to the effect of reionization on the polarized large-scale CMB anisotropies, reionization generates CMB temperature anisotropies through the kinetic Sunyaev-Zeldovich (kSZ) effect (Sunyaev & Zeldovich 1980), caused by the Doppler shift of photons scattering off electrons moving with bulk velocities. Simulations have shown that early homogeneous and patchy reionization scenarios differently affect the shape of the kSZ power spectrum, allowing us to place constraints on the reionization history (e.g., McQuinn et al. 2005; Aghanim et al. 2008). Zahn et al. (2012) derived the first constraints on the epoch of reionization from the combination of kSZ and low- ℓ CMB polarization, specifically using the low- ℓ polarization power spectrum from WMAP and the very high multipoles of the temperature angular power spectrum from the South Pole Telescope (SPT, Reichardt et al. 2012). However one should keep in mind that kSZ signal is complicated to predict and depends on detailed astrophysics which makes the constraints on reionization difficult to interpret (Mesinger et al. 2012).

In this paper, we investigate constraints on the epoch of reionization coming from *Planck*. Section 2 first briefly describes the pre-2016 data and likelihood used in this paper, which are presented in detail in Planck Collaboration Int. XLVI (2016). In Sect. 3 we then present the parameterizations we adopt for the ionization fraction, describing the reionization history as a function of redshift. In Sect. 4, we show the results obtained from the CMB observables (i.e., the optical depth τ and the amplitude of the kSZ effect) in the case of “instantaneous” reionization. Section 5 presents results based on the CMB measurements by considering different models for the ionization history. In particular, we derive limits on the reionization redshift and duration. Finally, in Sect. 6, we derive the ionization fraction as a function of redshift and discuss how our results relate to other astrophysical constraints.

2. Data and likelihood

2.1. Data

The present analysis is based on the pre-2016 full mission intensity and polarization *Planck*-HFI maps at 100 and 143 GHz. The data processing and the beam description are the same as in the *Planck* 2015 release and have been detailed in Planck Collaboration VII (2016). *Planck*-HFI polarization maps are constructed from the combination of polarized detectors that have fixed polarization direction. The *Planck* scanning strategy produces a relatively low level of polarization angle measurement redundancy on the sky, resulting in a high level of I - Q - U mixing, as shown in Planck Collaboration VIII (2016). As a consequence, any instrumental mismatch between detectors from the same frequency channel produces leakage from intensity to polarization. This temperature-to-polarization leakage was at one point the main systematic effect present in the *Planck*-

¹*Planck* (<http://www.esa.int/Planck>) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states and led by Principal Investigators from France and Italy, telescope reflectors provided through a collaboration between ESA and a scientific consortium led and funded by Denmark, and additional contributions from NASA (USA).

HFI data, and prevented robust low- ℓ polarization measurements from being included in the previous *Planck* data releases.

The maps that we use here differ in some respects from those data released in 2015. The updated mapmaking procedure, presented in [Planck Collaboration Int. XLVI \(2016\)](#), now allows for a significant reduction of the systematic effects in the maps. In particular, the relative calibration within a channel is now accurate to better than 0.001 %, which ensures a very low level of gain-mismatch between detectors. The major systematic effect that remains in the pre-2016 maps is due to imperfections of the correction for nonlinearity in the analogue-to-digital converters (ADCs) but produces very low level of residuals in the maps. In addition to the 100 GHz and 143 GHz maps, we also make use of 30 GHz LFI data ([Planck Collaboration II 2016](#)) and 353 GHz HFI data to remove polarized foregrounds.

Using the pre-2016 end-to-end simulations, we show that the power spectrum bias induced by the remaining nonlinearities is very small and properly accounted for in the likelihood. Figure 1 shows the bias (in the quantity $\mathcal{D}_\ell \equiv \ell(\ell+1)C_\ell/2\pi$, where C_ℓ is the conventional power spectrum) computed as the mean of the EE cross-power spectra from simulated maps, including realistic noise and systematic effects without and with Galactic foregrounds. In the latter case, the foregrounds are removed for each simulation using the 30 GHz and 353 GHz maps as templates for synchrotron and dust, respectively. The resulting bias in the EE 100 \times 143 cross-power spectrum can be used to correct the measured cross-spectrum, but in fact has very little impact on the likelihood.

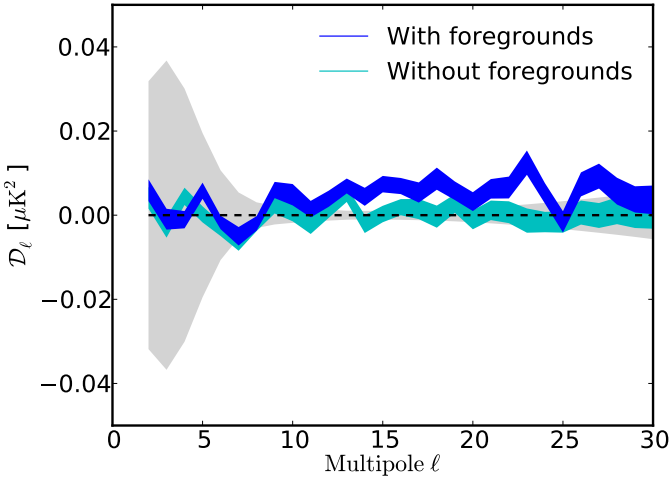


Fig. 1. Bias in the 100 \times 143 cross-power spectrum computed from simulations, including instrumental noise and systematic effects, with or without foregrounds (dark blue and light blue), compared to the cosmic variance level (in grey).

Furthermore, we use end-to-end simulations to propagate the systematic uncertainties to the cross-power spectra and all the way to the cosmological parameters. Figure 2 shows the impact on the variance due to the inclusion of the main ADC nonlinearity systematic effect, compared to realistic noise and cosmic variance. The resulting C_ℓ covariance matrix is estimated from these Monte Carlos. In the presence of such systematic effects, the variance of the C_ℓ is shown to be higher by roughly a factor of 2 compared to the pure noise case.

Polarized foregrounds at *Planck*-HFI frequencies are essentially dominated by Galactic dust emission, but also in-

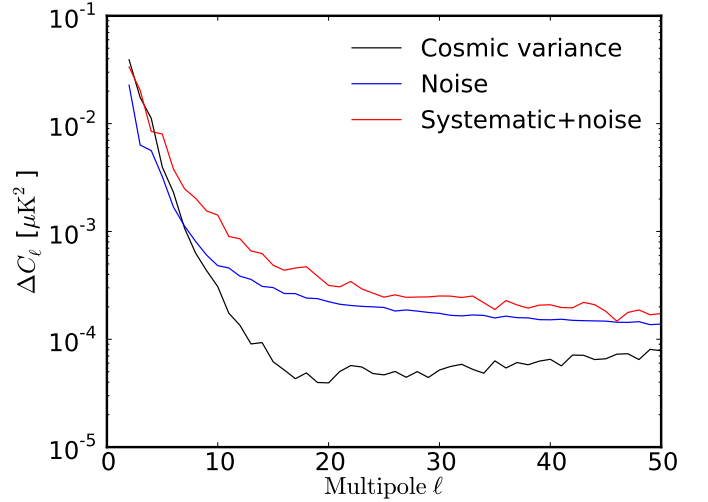


Fig. 2. Variance of the 100 \times 143 EE cross-power spectrum for simulations, including instrumental noise and noise plus systematic effects, compared to cosmic variance.

clude a small contribution from synchrotron emission. We use the 353 GHz and 30 GHz *Planck* maps as templates to subtract dust and synchrotron, respectively, using a single coefficient for each component over 95 % of the sky (see [Planck Collaboration IX 2016](#); [Planck Collaboration X 2016](#)). However, foreground residuals in the maps are still dominant over the CMB polarized signal near the Galactic plane. We therefore apply a very conservative mask, based on the amplitude of the polarized dust emission, which retains 50 % of the sky for the cosmological analysis. Outside this mask, the foreground residuals are found to be lower than 0.3 and 0.4 μK in Q and U Stokes polarization maps at 100 and 143 GHz, respectively. We have checked that our results are very stable when using a larger sky fraction of 60 %.

In this paper, we also make use of the constraints derived from the observation of the Gunn-Peterson effect on high-redshift quasars. As suggested by [Fan et al. \(2006a\)](#), these measurements show that the Universe was almost fully reionized at redshift $z \simeq 6$. We later discuss the results obtained with and without imposing a prior on the redshift of the end of reionization.

2.2. Likelihood

For temperature anisotropies, we use the combined *Planck* likelihood (hereafter “PlanckTT”), which includes the TT power spectrum likelihood at multipoles $\ell > 30$ (using the Plik code) and the low- ℓ temperature-only likelihood based on the CMB map recovered from the component-separation procedure (specifically Commander) described in detail in [Planck Collaboration XI \(2016\)](#).

For polarization, we use the *Planck* low- ℓ EE polarization likelihood (hereafter lollipop), a cross-spectra-based likelihood approach described in detail in [Mangilli et al. \(2015\)](#) and applied to *Planck* data as discussed here in Appendix A. The multipole range used is $\ell = 4\text{--}20$. Cross-spectra are estimated using the pseudo- C_ℓ estimator Xpol (a generalization to polarization of the algorithm presented in [Tristram et al. 2005](#)). For a full-sky analysis, the statistics of the reconstructed C_ℓ are given by a χ^2 distribution that is uncorrelated between multipoles. For a cut-sky analysis, the distribution is more complex and

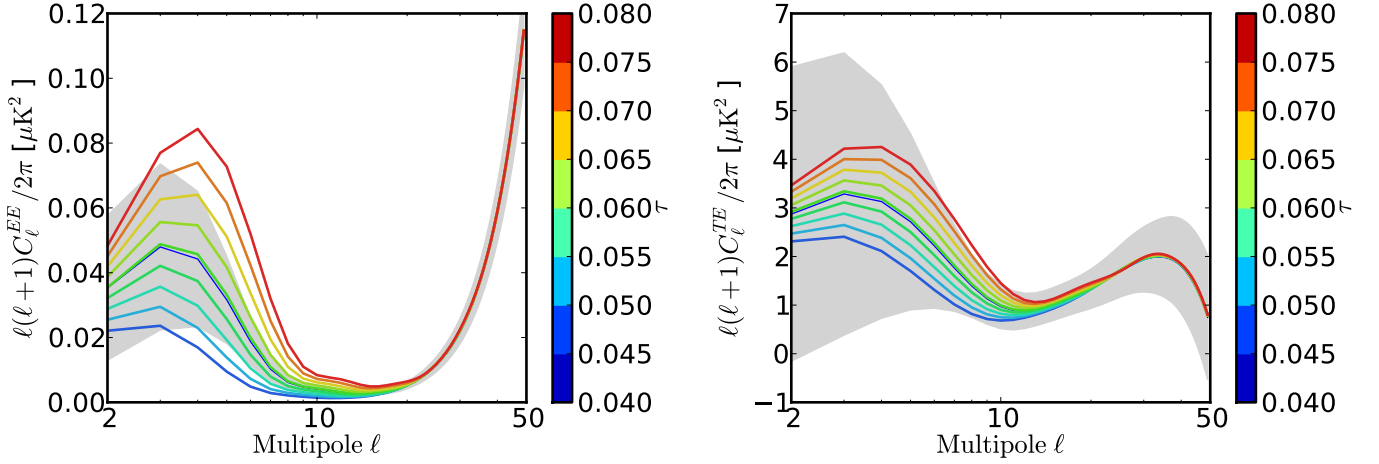


Fig. 3. EE and TE power spectra for various τ values ranging from 0.04 to 0.08. The ionization fraction is modelled using a redshift-symmetric tanh function with $\delta z = 0.5$. Grey bands represent the cosmic variance (full-sky) associated with the $\tau = 0.06$ model.

includes ℓ -to- ℓ correlations. Hamimeche & Lewis (2008) proposed an approximation of the likelihood for cut-sky auto-power spectra that was adapted by Mangilli et al. (2015) to be suitable for cross-spectra. Cross-spectra between independent data sets show common sky signal, but are not biased by the noise because this should be uncorrelated. This approximation assumes that any systematic residuals are *not* correlated between the different data sets; We have shown using realistic simulations (including *Planck*-HFI noise characteristics and systematic effect residuals), that the bias in the cross-spectra is very small and can be corrected for at the power-spectrum level. Nevertheless, we choose to remove the first two multipoles ($\ell = 2$ and $\ell = 3$), since they may still be partially contaminated by systematics. Using those simulations, we derive the C_ℓ covariance matrix used in the likelihood, which propagates both the noise and the systematic uncertainties. For the astrophysical interpretation, the power-spectra are estimated with a PCL estimate which is more conservative. Indeed, it gives a slightly larger distribution on τ than a QML estimator but is less sensitive to the limited number of simulations available for the analysis.

With *Planck* sensitivity in polarization, the results from the low- ℓ EE power spectrum dominate the constraints compared to the TE power spectrum, as can be seen in Fig. 3. This is because of the relatively larger cosmic variance for TE (arising from the temperature term) and the intrinsically weaker dependence on τ ($\propto \tau$ compared with τ^2 for EE), as well as the fact that there is only partial correlation between T and E . As a consequence, we do not consider the TE data in this analysis. Furthermore, we do not make use of the high- ℓ likelihoods in EE and TE from *Planck*, since they do not carry additional information on reionization parameters.

Planck temperature observations are complemented at smaller angular scales by measurements from the ground-based Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT). As explained in Planck Collaboration XI (2016), the high- ℓ likelihood (hereafter VHL) includes ACT power spectra at 148 and 218 GHz (Das et al. 2014), with a revised binning (described in Calabrese et al. 2013) and final beam estimates (Hasselfield et al. 2013), together with SPT measurements in the range $2000 < \ell < 13\,000$ from the 2540 deg² SPT-SZ survey at 95, 150, and 220 GHz (George et al. 2015). To assess the consistency between these data sets, we extend

the *Planck* foreground models up to $\ell = 13\,000$, with additional nuisance parameters for ACT and SPT (as described in Planck Collaboration XIII 2016). We use the same models for cosmic infrared background (CIB) fluctuations, the thermal SZ (tSZ) effect, kSZ effect, and CIB \times tSZ components. The kSZ template used in the *Planck* 2015 results assumed homogeneous reionization. In order to investigate inhomogeneous reionization, we have modified the kSZ template when necessary, as discussed in Sect. 4.2.

We use the CMB lensing likelihood (Planck Collaboration XV 2016) in addition to the CMB anisotropy likelihood. The lensing information can be used to break the degeneracy between the normalization of the initial power spectrum A_s and τ (as discussed in Planck Collaboration XIII 2016). Despite this potential for improvement, we show in Sect. 4.1 that *Planck*'s low- ℓ polarization signal-to-noise ratio is sufficiently high that the lensing does not bring much additional information for the reionization constraints.

The *Planck* reference cosmology used in this paper corresponds to the PlanckTT+lowP+lensing best fit, as described in table 4, column 2 of Planck Collaboration XIII (2016), namely $\Omega_b h^2 = 0.02226$, $\Omega_c h^2 = 0.1197$, $\Omega_m = 0.308$, $n_s = 0.9677$, $H_0 = 67.81 \text{ km s}^{-1} \text{ Mpc}^{-1}$, for which $Y_p = 0.2453$. This best-fit model comes from the combination of three *Planck* likelihoods: the temperature power spectrum likelihood at high ℓ ; the “lowP” temperature+polarization likelihood, based on the foreground-cleaned LFI 70 GHz polarization maps, together with the temperature map from the Commander component-separation algorithm; and the power spectrum of the lensing potential as measured by *Planck*.

3. Parametrization of reionization history

The epoch of reionization (EoR) is the period during which the cosmic gas transformed from a neutral to ionized state at the onset of the first sources. Details of the transition are thus strongly connected to many fundamental questions in cosmology, such as what were the properties of the first galaxies and the first (mini-)quasars, how did the formation of very metal-poor stars proceed, etc. We certainly know that, at some point, luminous sources started emitting ultraviolet ra-

diation that reionized the neutral regions around them. After a sufficient number of ionizing sources had formed, the average ionized fraction of the gas in the Universe rapidly increased until hydrogen became fully ionized. Empirical, analytic, and numerical models of the reionization process have highlighted many pieces of the essential physics that led to the birth to the ionized intergalactic medium (IGM) at late times (Couchman & Rees 1986; Miralda-Escude & Ostriker 1990; Meiksin & Madau 1993; Aghanim et al. 1996; Gruzinov & Hu 1998; Madau et al. 1999; Gnedin 2000; Barkana & Loeb 2001; Ciardi et al. 2003; Furlanetto et al. 2004; Pritchard et al. 2010; Pandolfi et al. 2011; Mitra et al. 2011; Iliev et al. 2014). Such studies provide predictions on the various reionization observables, including those associated with the CMB.

The most common physical quantity used to characterize reionization is the Thomson scattering optical depth defined as

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T c dt', \quad (1)$$

where n_e is the number density of free electrons at time t' , σ_T is the Thomson scattering cross-section, t_0 is the time today, $t(z)$ is the time at redshift z , and we can use the Friedmann equation to convert dt to dz . The reionization history is conveniently expressed in terms of the ionized fraction $x_e(z) \equiv n_e(z)/n_H(z)$ where $n_H(z)$ is the hydrogen number density. In practice, the CMB is sensitive to the average over all sky directions of $x_e(1 + \delta_b)$ (where δ_b denotes the baryon overdensity). The IGM is likely to be very inhomogeneous during reionization process, with ionized bubbles embedded in neutral surroundings, which would impact the relation between the optical depth and the reionisation parameters (see Liu et al. 2015) at a level which is neglected in this paper.

In this study, we define the redshift of reionization, $z_{\text{re}} \equiv z_{50\%}$, as the redshift at which $x_e = 0.5 \times f$. Here the normalization, $f = 1 + f_{\text{He}} = 1 + n_{\text{He}}/n_{\text{H}}$, takes into account electrons injected into the IGM by the first ionization of helium (corresponding to 25 eV), which is assumed to happen roughly at the same time as hydrogen reionization. We define the beginning and the end of the EoR by the redshifts $z_{\text{beg}} \equiv z_{10\%}$ and $z_{\text{end}} \equiv z_{99\%}$ at which $x_e = 0.1 \times f$ and $0.99 \times f$, respectively. The duration of the EoR is then defined as $\Delta z = z_{10\%} - z_{99\%}$.² Moreover, to ensure that the Universe is fully reionized at low redshift, we impose the condition that the EoR is completed before the second helium reionization phase (corresponding to 54 eV), noting that it is commonly assumed that quasars are necessary to produce the hard photons needed to ionize helium. To be explicit about how we treat the lowest redshifts we assume that the full reionization of helium happens fairly sharply at $z_{\text{He}} = 3.5$ (Becker et al. 2011), following a transition of hyperbolic tangent shape with width $\delta z = 0.5$. While there is still some debate on whether helium reionization could be inhomogeneous and extended (and thus have an early start, Worseck et al. 2014), we have checked that varying the helium reionization redshift between 2.5 and 4.5 changes the total optical depth by less than 1 %.

The simplest and most widely-used parameterizations describes the EoR as a step-like transition between an essentially vanishing ionized fraction³ x_e at early times, to a value of unity at low redshifts. When calculating the effect on anisotropies it is

necessary to give a non-zero width to the transition, and it can be modelled using a tanh function (Lewis 2008):

$$x_e(z) = \frac{f}{2} \left[1 + \tanh \left(\frac{y - y_{\text{re}}}{\delta y} \right) \right], \quad (2)$$

where $y = (1 + z)^{3/2}$ and $\delta y = \frac{3}{2}(1 + z)^{1/2} \delta z$. The key parameters are thus z_{re} , which measures the redshift at which the ionized fraction reaches half its maximum and a width δz . The tanh parameterization of the EoR transition allows us to compute the optical depth of Eq. (1) for a one-stage almost redshift-symmetric⁴ reionization transition, where the redshift interval between the onset of the reionization process and its half completion is (by construction) equal to the interval between half completion and full completion. In this parameterization, the optical depth is mainly determined by z_{re} and almost degenerate with the width δz . This is the model used in the *Planck* 2013 and 2015 cosmological papers, for which we have fixed $\delta z = 0.5$ (corresponding to $\Delta z = 1.73$). In this case, we usually talk about “instantaneous” reionization.

A redshift-asymmetric parameterization is a better, more flexible description of numerical simulations of the reionization process (e.g., Ahn et al. 2012; Park et al. 2013; Douspis et al. 2015). A function with this behaviour is also suggested by the constraints from ionizing background measurements of star-forming galaxies and from low-redshift line-of-sight probes such as quasars, Lyman- α emitters, or γ -ray bursts (Faisst et al. 2014; Chornock et al. 2014; Ishigaki et al. 2015; Robertson et al. 2015; Bouwens et al. 2015). The two simplest choices of redshift-asymmetric parameterizations are polynomial or exponential functions of redshift (Douspis et al. 2015). These two parameterizations are in fact very similar, and we adopt here a power law defined by two parameters: the redshift at which reionization ends (z_{end}); and the exponent α . Specifically we have

$$x_e(z) = \begin{cases} f & \text{for } z < z_{\text{end}}, \\ f \left(\frac{z_{\text{early}} - z}{z_{\text{early}} - z_{\text{end}}} \right)^\alpha & \text{for } z > z_{\text{end}}. \end{cases} \quad (3)$$

In the following, we fix $z_{\text{early}} = 20$, the redshift around which the first emitting sources form, and at which we smoothly match $x_e(z)$ to the ionized fraction left over from recombination. We checked that our results are not sensitive to the precise value of z_{early} , as long as it is not dramatically different.

Non-parametric reconstructions of the ionization fraction have also been proposed to probe the reionization history. Such methods are based on exploring reionization parameters in bins of redshift (Lewis et al. 2006). They should be particularly useful for investigating exotic reionization histories, e.g., double reionization (Cen 2003). However, the CMB large-scale ($\ell \lesssim 10$) polarization anisotropies are mainly sensitive to the overall value of the optical depth, which determines the amplitude of the reionization bump in the EE power spectrum (see Fig. 3). We have estimated the impact on C_ℓ^{EE} for the two different models (tanh and power law) having the same $\tau = 0.06$ and found differences of less than 4 % for $\ell < 10$. Even for a double reionization model, Fig. 4 shows that the impact on C_ℓ^{EE} is quite weak, given the actual measured value of τ , and cannot be distinguished relative to the cosmic variance spread

²The reason this is not defined symmetrically is that in practice we have tighter constraints on the end of reionization than on the beginning.

³The ionized fraction is actually matched to the relic free electron density from recombination, calculated using *recfast* Seager et al. (2000).

⁴For convenience, we refer to this parameterization as “redshift symmetric” in the rest of the paper, even although it is actually symmetric in y rather than z . The asymmetry is maximum in the instantaneous case, but the difference in x_e values around, for example, $z_{\text{re}} = 8 \pm 1$, is less than 1 %.

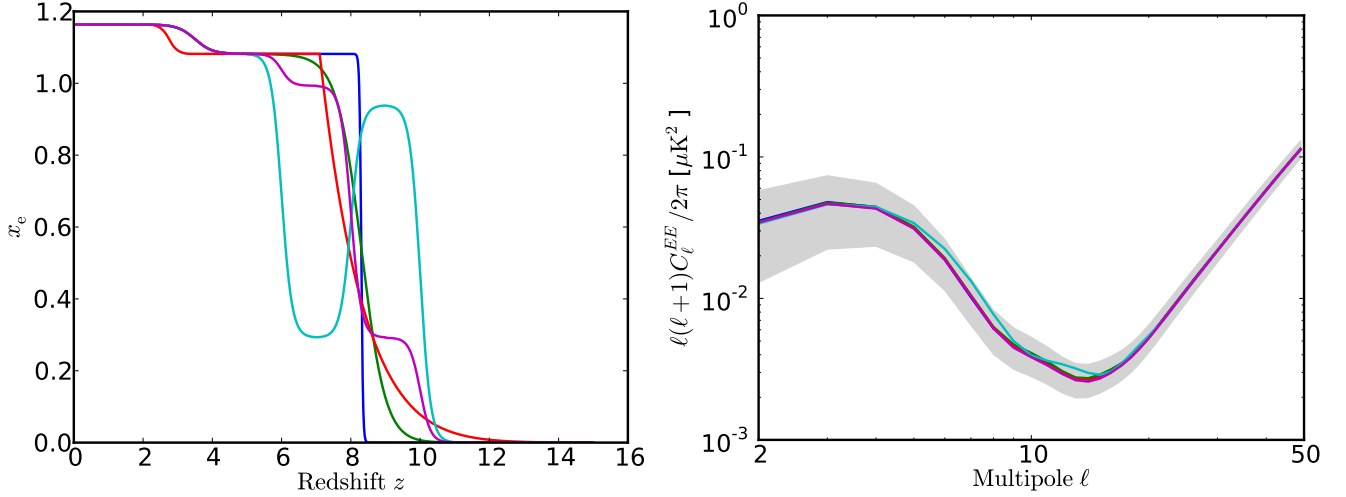


Fig. 4. *Left:* Evolution of the ionization fraction for several functions, all having the same optical depth, $\tau = 0.06$: green and blue are for redshift-symmetric instantaneous ($\delta z = 0.05$) and extended reionization ($\delta z = 0.7$), respectively; red is an example of a redshift-asymmetric parameterization; and light blue and magenta are examples of an ionization fraction defined in redshift bins, with two bins inverted between these two examples. *Right:* corresponding EE power spectra with cosmic variance in grey. All models have the same optical depth $\tau = 0.06$ and are essentially indistinguishable at the reionization bump scale.

(i.e., even for a full-sky experiment). We also checked that *Planck* data do not allow for model-independent reconstruction of x_e in redshift bins. Principal component analysis has been proposed as an explicit approach to try to capture the details of the reionization history in a small set of parameters (Hu & Holder 2003; Mortonson & Hu 2008). Although these methods are generally considered to be non-parametric, they are in fact based on a description of $x_e(z)$ in bins of redshift, expanded around a given fiducial model for C_ℓ^{EE} . Moreover, the potential bias on the τ measurement when analysing a more complex reionization history using a simple sharp transition model (Holder et al. 2003; Colombo & Pierpaoli 2009) is considerably reduced for the (lower) τ values as suggested by the *Planck* results. Consequently, we do not consider the non-parametric approach further.

4. Measuring reionization observables

Reionization leaves imprints in the CMB power spectra, both in polarization at very large scales and in intensity via the suppression of TT power at higher ℓ . Reionization also affects the kSZ effect, due to the re-scattering of photons off newly liberated electrons. We sample from the space of possible parameters with MCMC exploration using CAMEL⁵. This uses an adaptive-Metropolis algorithm to generate chains of samples for a set of parameters.

4.1. Large-scale CMB polarization

Thomson scattering between the CMB photons and free electrons generates linear polarization from the quadrupole moment of the CMB radiation field at the scattering epoch. This occurs at recombination and also during the epoch of reionization. Re-scattering of the CMB photons at reionization generates an additional polarization anisotropy at large angular scales, because the horizon size at this epoch subtends a much larger angular size. The multipole location of this additional anisotropy (essen-

tially a bump) in the EE and TE angular power spectra relates to the horizon size at the new “last-rescattering surface” and thus depends on the redshift of reionization. The height of the bump is a function of the optical depth or, in other words, of the history of the reionization process. Such a signature (i.e., a polarization bump at large scales) was first observed by WMAP, initially in the TE angular power spectrum (Kogut et al. 2003), and later in combination with all power spectra (Hinshaw et al. 2013).

In Fig. 3 we show for the “instantaneous” reionization case (specifically the redshift-symmetric parameterization with $\delta z = 0.5$) power spectra for the E -mode polarization power spectrum C_ℓ^{EE} and the temperature-polarization cross-power spectrum C_ℓ^{TE} . The curves are computed with the CLASS Boltzmann solver (Lesgourgues 2011) using τ values ranging from 0.04 to 0.08. For the range of optical depth considered here and given the amount of cosmic variance, the TE spectrum has only a marginal sensitivity to τ , while in EE the ability to distinguish different values of τ is considerably stronger.

In Fig. 4 (left panel), the evolution of the ionized fraction x_e during the EoR is shown for five different parameterizations of the reionization history, all yielding the same optical depth $\tau = 0.06$. Despite the differences in the evolution of the ionization fraction, the associated C_ℓ^{EE} curves (Fig. 4, right panel) are almost indistinguishable. This illustrates that while CMB large-scale anisotropies in polarization are only weakly sensitive to the details of the reionization history, they can nevertheless be used to measure the reionization optical depth, which is directly related to the amplitude of the low- ℓ bump in the E -mode power spectrum.

We use the *Planck* data to provide constraints on the Thomson scattering optical depth for “instantaneous” reionization. Figure 5 shows the posterior distributions for τ obtained with the different data sets described in Sect. 2 and compared to the 2015 PlanckTT+lowP results (Planck Collaboration XIII 2016). We show the posterior distribution for the low- ℓ *Planck* polarized likelihood (lollipop) and in combination with the high- ℓ *Planck* likelihood in temperature (PlanckTT). We also consider the effect of adding the SPT and ACT likelihoods

⁵available at camel.in2p3.fr

(VHL) and the *Planck* lensing likelihood, as described in [Planck Collaboration XV \(2016\)](#).

The different data sets show compatible constraints on the optical depth τ . The comparison between posteriors indicates that the optical depth measurement is driven by the low- ℓ likelihood in polarization (i.e., *lollipop*). The *Planck* constraints on τ for a Λ CDM model when considering the standard “instantaneous” reionization assumption (symmetric model with fixed $\delta z = 0.5$), for the various data combinations are:

$$\tau = 0.053^{+0.014}_{-0.016}, \quad \text{lollipop}^6; \quad (4)$$

$$\tau = 0.058^{+0.012}_{-0.012}, \quad \text{lollipop+PlanckTT}; \quad (5)$$

$$\tau = 0.058^{+0.011}_{-0.012}, \quad \text{lollipop+PlanckTT+lensing}; \quad (6)$$

$$\tau = 0.054^{+0.012}_{-0.013}, \quad \text{lollipop+PlanckTT+VHL}. \quad (7)$$

We can see an improvement of the posterior width when adding temperature anisotropy data to the *lollipop* likelihood. This comes from the fact that the temperature anisotropies help to fix other Λ CDM parameters, in particular the normalization of the initial power spectrum A_s , and its spectral index, n_s . CMB lensing also helps to reduce the degeneracy with A_s , while getting rid of the tension with the phenomenological lensing parameter A_L when using PlanckTT only (see [Planck Collaboration XIII 2016](#)), even if the impact on the error bars is small. Comparing the posteriors in Fig. 6 with the constraints from PlanckTT alone (see figure 45 in [Planck Collaboration XI 2016](#)) shows that indeed, the polarization likelihood is sufficiently powerful that it breaks the degeneracy between n_s and τ . The impact on other Λ CDM parameters is small, typically below 0.3σ (as shown more explicitly in Appendix B). The largest changes are for τ and A_s , where the *lollipop* likelihood dominates the constraint. The parameter σ_8 shifts towards slightly smaller values by about 1σ . This is in the right direction to help resolve some of the tension with cluster abundances and weak galaxy lensing measurements, discussed in [Planck Collaboration XX \(2014\)](#) and [Planck Collaboration XIII \(2016\)](#); however, some tension still remains.

Combining with VHL data gives compatible results, with consistent error bars. The slight shift toward lower τ value (by 0.3σ) is related to the fact that the PlanckTT likelihood alone pushes towards higher τ values (see [Planck Collaboration XIII 2016](#)), while the addition of VHL data helps to some extent in reducing the tension on τ between high- ℓ and low- ℓ polarization.

As mentioned earlier, astrophysics constraints from measurements of the Gunn-Peterson effect provide strong evidence that the IGM was highly ionized by a redshift of $z \simeq 6$. This places a lower limit on the optical depth (using Eq. 1), which in the case of instantaneous reionization in the standard Λ CDM cosmology corresponds to $\tau = 0.038$.

4.2. Kinetic Sunyaev-Zeldovich effect

The Thomson scattering of CMB photons off ionized electrons induces secondary anisotropies at different stages of the reionization process. In particular, we are interested here in the effect of photons scattering off electrons moving with bulk velocity, which is called the “kinetic Sunyaev-Zeldovich” or kSZ effect. It is common to distinguish between the “homogeneous” kSZ effect, arising when the reionization is complete (e.g., [Ostriker & Vishniac 1986](#)), and “patchy” (or inhomogeneous) reionization (e.g., [Aghanim et al. 1996](#)), which arises

⁶In this case only, other Λ CDM parameters are held fixed, including A_s exp (-2τ) .

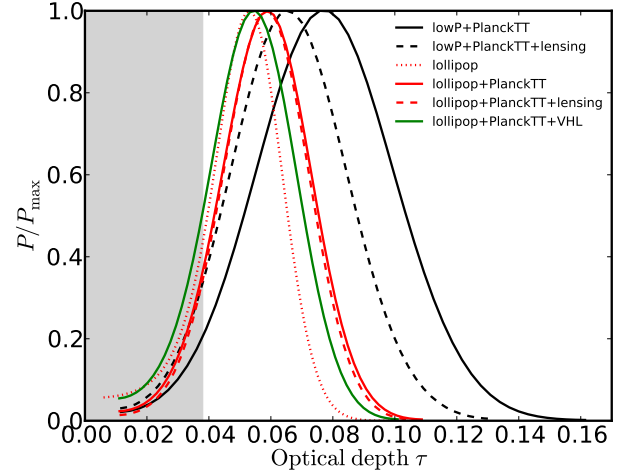


Fig. 5. Posterior distribution for τ from the various combinations of *Planck* data. The grey band shows the lower limit on τ from the Gunn-Peterson effect.

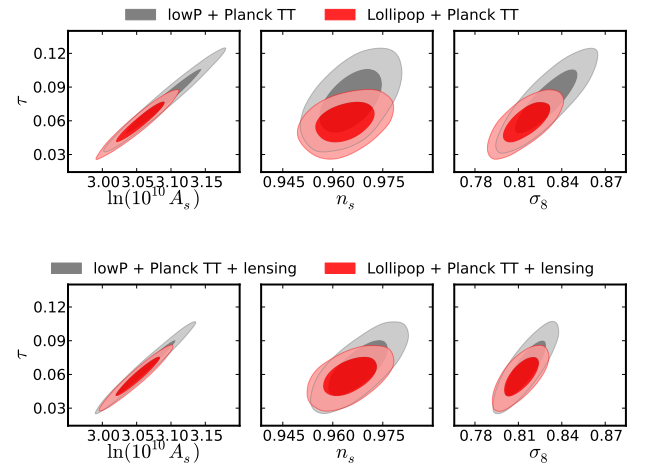


Fig. 6. Constraints on τ , A_s , n_s , and σ_8 for the Λ CDM cosmology from PlanckTT, showing the impact of replacing the lowP likelihood from *Planck* 2015 release with the new *lollipop* likelihood. The top panels show results without lensing, while the bottom panels are with lensing.

during the process of reionization, from the proper motion of ionized bubbles around emitting sources. These two components can be described by their power spectra, which can be computed analytically or derived from numerical simulations. In [Planck Collaboration XI \(2016\)](#), we used a kSZ template based on homogeneous simulations, as described in [Trac et al. \(2011\)](#).

In the following, we assume that the kSZ power spectrum is given by

$$\mathcal{D}_\ell^{\text{kSZ}} = \mathcal{D}_\ell^{\text{h-kSZ}} + \mathcal{D}_\ell^{\text{p-kSZ}}, \quad (8)$$

where $\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi$ and the superscripts “h-kSZ” and “p-kSZ” stand for “homogeneous” and “patchy” reionization, respectively. For the homogeneous reionization, we use the kSZ template power spectrum given by [Shaw et al. \(2012\)](#) calibrated with a simulation that includes the effects of cooling and star-formation (which we label “CSF”). For the patchy reionization kSZ effect we use the fiducial model of [Battaglia et al. \(2013\)](#).

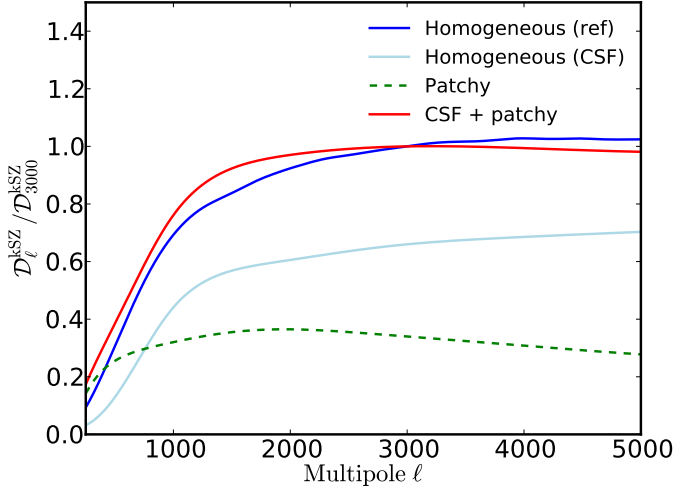


Fig. 7. Power spectrum templates for the kSZ effect. The different lines correspond to: homogeneous reionization as used in Planck Collaboration XI (2016) (dark blue), based on Trac et al. (2011); “CSF” (light blue), which is a homogeneous reionization model from Shaw et al. (2012); Patchy (green dashed) based on patchy reionization model from Battaglia et al. (2013); and the sum of CSF and patchy (red).

In the range $\ell = 1000$ – 7000 , the shape of the kSZ power spectrum is relatively flat and does not vary much with the detailed reionization history. The relative contributions (specifically “CSF” and “patchy”) to the kSZ power spectrum are shown in Fig 7 and compared to the “homogeneous” template used in Planck Collaboration XI (2016), rescaled to unity at $\ell = 3000$.

The kSZ power spectrum amplitude does depend on the cosmological parameters (Shaw et al. 2012; Zahn et al. 2012). To deal with this, we adopt the scalings from Shaw et al. (2012), which gives the amplitude at $\ell = 3000$, $A_{\text{kSZ}} \equiv \mathcal{D}_{\ell=3000}^{\text{kSZ}}$:

$$A_{\text{kSZ}} \propto \left(\frac{h}{0.7}\right)^{1.7} \left(\frac{\sigma_8}{0.8}\right)^{4.5} \left(\frac{\Omega_b}{0.045}\right)^{2.1} \left(\frac{0.27}{\Omega_m}\right)^{0.44} \left(\frac{0.96}{n_s}\right)^{0.19}. \quad (9)$$

The amplitude of the kSZ power spectrum at $\ell = 3000$ for the fiducial cosmology, A_{kSZ} is another observable of the reionization history that can be probed by CMB data. Its scalings with the reionization redshift and the duration of the EoR can be extracted from simulations. We assume for the patchy and homogeneous kSZ effect, the scalings of Battaglia et al. (2013) and Shaw et al. (2012), respectively. For the Planck base Λ CDM cosmology given in Sect. 2.2, we find (in μK^2):

$$A_{\text{kSZ}}^h = 2.02 \times \left(\frac{\tau}{0.076}\right)^{0.44}; \quad (10)$$

$$A_{\text{kSZ}}^p = 2.03 \times \left[\left(\frac{1+z_{\text{re}}}{11}\right) - 0.12\right] \left(\frac{z_{25\%} - z_{75\%}}{1.05}\right)^{0.51}. \quad (11)$$

For the measured value $\tau = 0.058 \pm 0.012$, Eqs. (10) and (11) give amplitudes for the homogeneous and patchy reionization contributions of $A_{\text{kSZ}}^h = 1.79 \mu\text{K}^2$ and $A_{\text{kSZ}}^p = 1.01 \mu\text{K}^2$, respectively.

For the multipole range of Planck, the amplitude of the kSZ spectrum is dominated by other foregrounds, including Galactic dust, point sources, CIB fluctuations, and the tSZ effect. Moreover, the Planck signal-to-noise ratio decreases rapidly above $\ell = 2000$, where the kSZ signal is maximal. This is why we cannot constrain the kSZ amplitude using Planck data

alone. Combining with additional data at higher multipoles helps to disentangle the different foregrounds. We explicitly use the band powers from SPT (George et al. 2015) and ACT (Das et al. 2014), covering the multipole range up to $\ell = 13000$.

Despite our best efforts to account for the details, the kSZ amplitude is weak and there are large uncertainties in the models (both homogeneous and patchy). Moreover, there are correlations between the different foreground components, coming both from the astrophysics (we use the same halo model to derive the power spectra for the CIB and for CIB \times tSZ as the one used for the kSZ effect) and from the adjustments in the data. We carried out several tests to check the robustness of the constraints on A_{kSZ} with respect to the template used for the CIB, CIB \times tSZ, and kSZ contributions. In particular, the CIB \times tSZ power spectrum amplitude is strongly anti-correlated with the kSZ amplitude and poorly constrained by the CMB data. As a consequence, if we neglect the CIB \times tSZ contribution, the kSZ amplitude measured in CMB data is substantially reduced, leading to an upper limit much lower than the one derived when including the CIB \times tSZ correlation. In the following discussion we consider only the more realistic case (and thus more conservative in terms of constraints on A_{kSZ}) where the CIB \times tSZ correlation contributes to the high- ℓ signal.

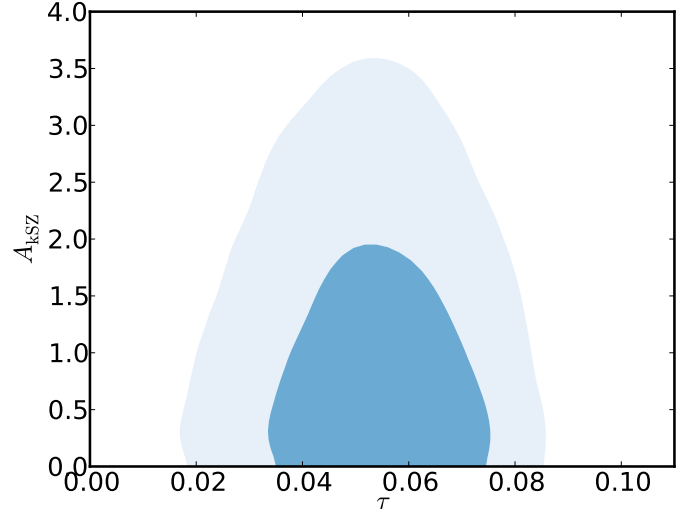


Fig. 8. 68 % and 95 % confidence intervals on the reionization optical depth, τ , and the amplitude of the kinetic SZ effect, A_{kSZ} , from the CMB (lollipop+PlanckTT+VHL).

We combine the Planck likelihoods in TT (PlanckTT) and from low- ℓ EE polarization (lollipop) with the very high- ℓ data from ACT and SPT (VHL), assuming a redshift-symmetric parameterization of the reionization. Figure 8 shows the 2D posterior distribution for τ and A_{kSZ} after marginalization over the other cosmological and nuisance parameters.

Figure 9 compares the constraints on the kSZ power at $\ell = 3000$, A_{kSZ} , obtained for three different kSZ templates: the “homogeneous” reionization template from Trac et al. (2011), which neglects contributions from inhomogeneous reionization; a more complex model “CSF & patchy,” including both homogeneous and patchy contributions; and a pure “patchy” template from Battaglia et al. (2013). We find very similar upper limits on A_{kSZ} , even in the case of pure patchy reionization.

Using the “CSF & patchy” model, the upper limit is

$$A_{\text{kSZ}} < 2.6 \mu\text{K}^2 \quad (95\% \text{ CL}). \quad (12)$$

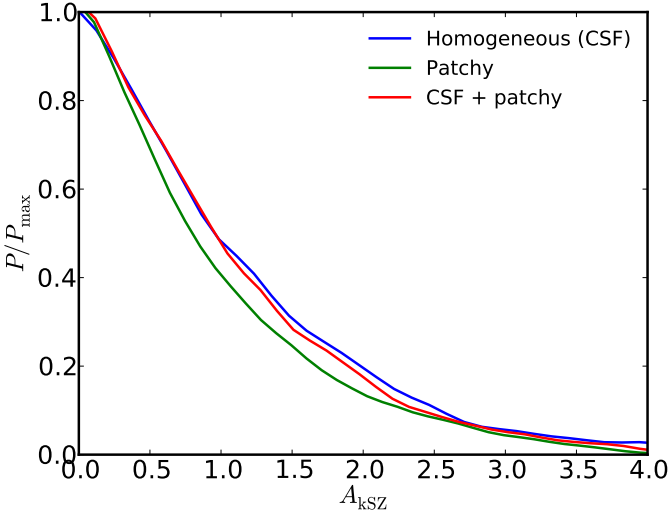


Fig. 9. Constraints on the kSZ amplitude at $\ell = 3000$ using lollipop+PlanckTT+VHL likelihoods. The three cases correspond to different kSZ templates.

Compared to *Planck* 2013 results, the maximum likelihood value $A_{\text{kSZ}} = 5.3^{+2.8}_{-1.9} \mu\text{K}^2$ (PlanckTT+WP+highL, Planck Collaboration XVI 2014) is reduced to an upper limit in this new analysis. The data presented here provide the best constraint to date on the kSZ power and is a factor of 2 lower than the limit reported in George et al. (2015). Our limit is certainly not in tension with the homogeneous kSZ template, which predicts $A_{\text{kSZ}} = 1.79 \mu\text{K}^2$. However, it does not leave much room for any additional kSZ power coming from patchy reionization.

Consistent with George et al. (2015), we find the total kSZ power to be stable against varying tSZ and CIB templates. We also find very little dependence on the choice of the kSZ template (Fig. 9). This confirms that there is only a modest amount of information in the angular shape of the kSZ signal with the current data.

5. Constraints on the reionization history

We now interpret our measurements of the reionization observables in terms of constraint on the reionization history. We mainly focus on the determination of the reionization redshift z_{re} and its duration $\Delta z = z_{\text{beg}} - z_{\text{end}}$. We show only the results for Δz greater than unity, which corresponds to approximately 90 Myr at redshift $z = 8$. We first begin by looking at constraints on the EoR for symmetric and asymmetric models using *Planck* data only (lollipop+PlanckTT). Then we introduce the VHL data and discuss additional constraints from the kSZ amplitude. In each case, we also derive the constraints that follow from postulating that reionization should be completed at a redshift of 6 (see Sect. 2.1), i.e., when imposing the prior $z_{\text{end}} > 6$.

5.1. Redshift-symmetric parameterization

We use the *Planck* CMB likelihoods in temperature (PlanckTT) and polarization (lollipop) to derive constraints on ΛCDM parameters, including the reionization redshift z_{re} and width Δz for a redshift-symmetric parameterization. Figure 10 shows (in blue) the posterior on z_{re} and Δz after marginalization over the other cosmological and nuisance parameters. As discussed in Sect. 3, the large-scale polarized CMB anisotropies are almost

insensitive to the width δz of the tanh function. We thus recover the degeneracy in the direction of Δz . Imposing an additional Gunn-Peterson constraint on the ionization fraction at very low redshift can break this degeneracy. This is illustrated in Fig. 10, where we show (in green) the results of the same analysis with an additional prior $z_{\text{end}} > 6$. In this case, we find $\delta z < 1.3$ at 95 % CL, which corresponds to a reionization duration ($z_{\text{beg}} - z_{\text{end}}$) of

$$\Delta z < 4.6 \quad (95 \% \text{ CL}). \quad (13)$$

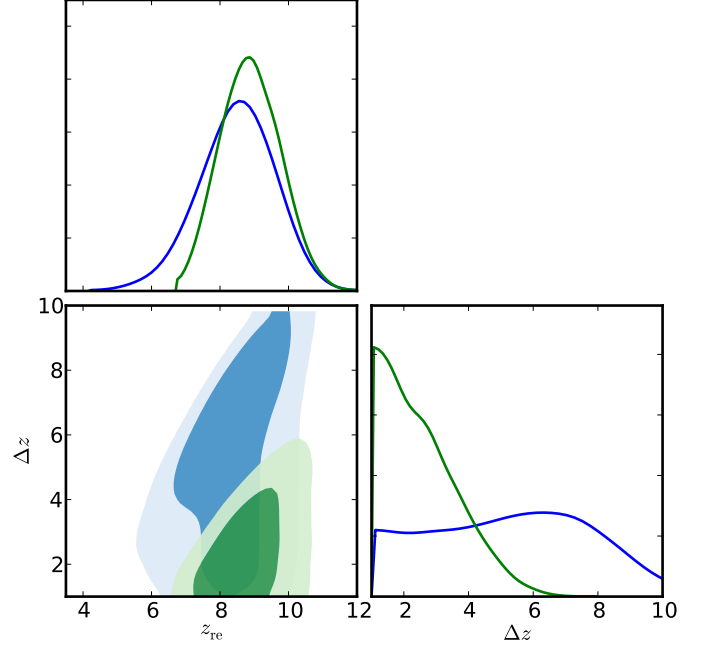


Fig. 10. Posterior distributions (in blue) of z_{re} and Δz for a redshift-symmetric parameterization using the CMB likelihoods in polarization and temperature (lollipop+PlanckTT). The green contours and lines show the distribution after imposing the additional prior $z_{\text{end}} > 6$.

The posterior distribution of z_{re} is shown in Fig. 10 after marginalizing over Δz , with and without the additional constraint $z_{\text{end}} > 6$. This suggests that the reionization process occurred at redshift

$$z_{\text{re}} = 8.5^{+1.0}_{-1.1} \quad (\text{uniform prior}), \quad (14)$$

$$z_{\text{re}} = 8.8^{+0.9}_{-0.9} \quad (\text{prior } z_{\text{end}} > 6). \quad (15)$$

This redshift is lower than the values derived previously from WMAP-9 data, in combination with ACT and SPT (Hinshaw et al. 2013), namely $z_{\text{re}} = 10.3 \pm 1.1$. It is also lower than the value $z_{\text{re}} = 11.1 \pm 1.1$ derived in Planck Collaboration XVI (2014), based on *Planck* 2013 data and the WMAP-9 polarization likelihood.

Although the uncertainty is now smaller, this new reionization redshift value is entirely consistent with the *Planck* 2015 results (Planck Collaboration XIII 2016) for PlanckTT+lowP alone, $z_{\text{re}} = 9.9^{+1.8}_{-1.6}$ or in combination with other data sets, $z_{\text{re}} = 8.8^{+1.3}_{-1.2}$ (specifically for PlanckTT+lowP+lensing+BAO) estimated with δz fixed to 0.5. The constraint from lollipop+PlanckTT when fixing δz to 0.5 is $z_{\text{re}} = 8.2^{+1.0}_{-1.2}$. This slightly lower value (compared to the one obtained when letting the reionization width be free) is explained

by the shape of the degeneracy surface. Allowing for larger duration when keeping the same value of τ pushes towards higher reionization redshifts; marginalizing over Δz thus shifts the posterior distribution to slightly larger z_{re} values.

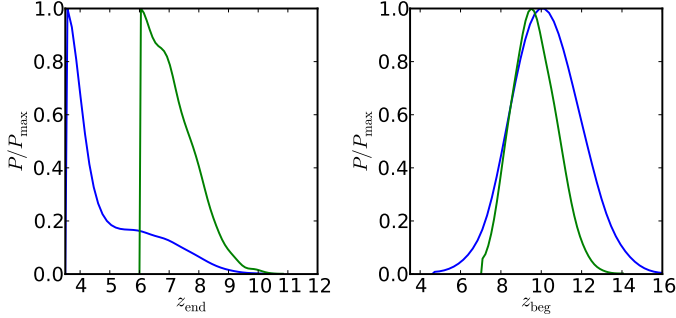


Fig. 11. Posterior distributions on the end and beginning of reionization, i.e., z_{end} and z_{beg} , using the redshift-symmetric parameterization without (blue) and with (green) the prior $z_{\text{end}} > 6$.

In addition to the posteriors for z_{re} and δz using the redshift-symmetric parameterization, the distributions of the end and beginning of reionization, z_{end} (i.e., $z_{99\%}$) and z_{beg} (i.e., $z_{10\%}$), are plotted in Fig. 11. In such a model, the end of reionization strongly depends on the constraint at low redshift. On the other hand, the constraints on z_{beg} depend only slightly on the low-redshift prior. These results show that the Universe is ionized at less than the 10 % level above $z = 9.4 \pm 1.2$.

5.2. Redshift-asymmetric parameterization

We now explore more complex reionization histories using the redshift-asymmetric parameterization of $x_e(z)$ described in Sect. 3. In the same manner as in Sect. 5.1, also examine the effect of imposing the additional constraint from the Gunn-Peterson effect.

The distributions of the two parameters, z_{end} and z_{beg} , are plotted in Fig. 12. With the redshift-asymmetric parameterization, we obtain $z_{\text{beg}} = 10.4^{+1.9}_{-1.6}$ (imposing the prior on z_{end}), which disfavors any major contribution to the ionized fraction from sources that could form as early as $z \gtrsim 15$.

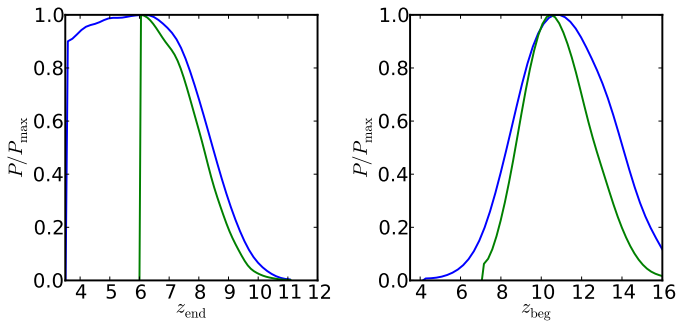


Fig. 12. Posterior distributions of z_{end} and z_{beg} using the redshift-asymmetric parameterization without (blue) and with (green) the prior $z_{\text{end}} > 6$.

In Fig. 13, we interpret the results in terms of reionization redshift and duration of the EoR, finding

$$z_{\text{re}} = 8.0^{+0.9}_{-1.1} \quad (\text{uniform prior}), \quad (16)$$

$$z_{\text{re}} = 8.5^{+0.9}_{-0.9} \quad (\text{prior } z_{\text{end}} > 6). \quad (17)$$

These values are within 0.4σ of the results for the redshift-symmetric model. For the duration of the EoR, the upper limits on Δz are

$$\Delta z < 10.2 \quad (95\% \text{ CL, uniform prior}), \quad (18)$$

$$\Delta z < 6.8 \quad (95\% \text{ CL, prior } z_{\text{end}} > 6). \quad (19)$$

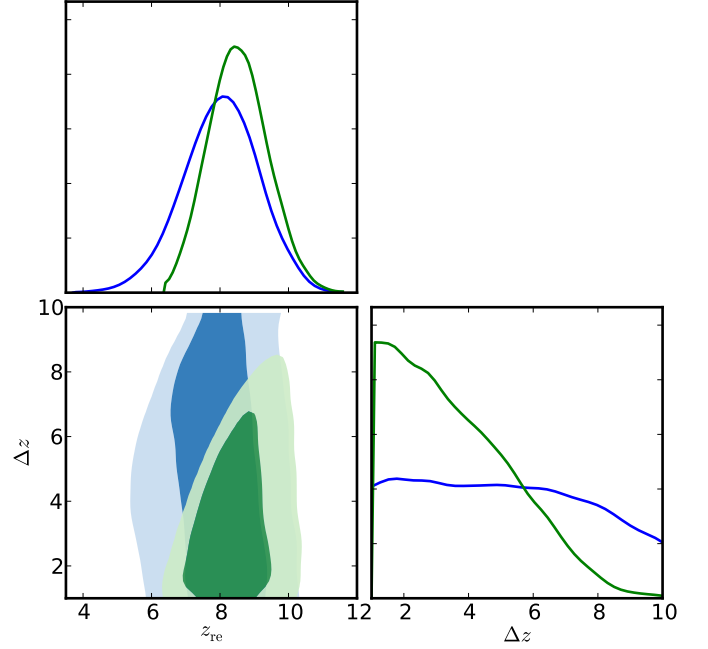


Fig. 13. Posterior distributions for z_{re} and Δz using the redshift-asymmetric parameterization without (blue) and with (green) the prior $z_{\text{end}} > 6$.

5.3. Combination with the kSZ effect

In order to try to obtain better constraints on the reionization width, we now make use of the additional information coming from the amplitude of the kinetic SZ effect. Since *Planck* alone is not able to provide accurate limits on the kSZ amplitude, we combine the *Planck* likelihoods in temperature and polarization with the measurements of the CMB TT power spectrum at high-resolution from the ACT and SPT experiments, “VHL.”

Using the redshift-symmetric model, when adding the VHL data, we recover essentially the same results as in Sect. 5.1. The reionization redshift is slightly lower, as suggested by the results on τ (see Eq. 7 and the discussion in Sect. 4.1). We also see the same degeneracy along the Δz direction.

With the addition of kSZ information, we are able to break the degeneracy with Δz . This might allow us to determine how much kSZ power originated during reionization (i.e., patchy kSZ) and how much at later times, when the Universe became fully ionized (i.e., homogeneous kSZ). We use the templates from Shaw et al. (2012) and Battaglia et al. (2013) for the homogeneous and patchy kSZ contributions, respectively, with the

dependency on Λ CDM cosmological parameters as described in Sect. 4.2. Those specific relations rely on a redshift-symmetric model for the description of the EoR. Note, however, that the results presented here are derived from specific simulations of the reionization process, and so explicit scalings need to be assumed, as discussed by Zahn et al. (2012) and George et al. (2015).

As described in Sect. 4.2, the amplitude of the kSZ power primarily depends on the duration of reionization, while the epoch is essentially constrained by the optical depth. Using the 2D distribution for τ and A_{kSZ} , as measured by *Planck* in combination with very high- ℓ temperature data (Fig. 8), we derive a 2D likelihood function for z_{re} and Δz . We can then sample the reionization parameters (the epoch z_{re} and duration Δz of the EoR), compute the associated optical depth and kSZ power and derive constraints based on the 2D likelihood. The allowed models in terms of z_{re} and Δz are shown in Fig. 14 (in blue). We also plot (in green) the same constraints with the additional prior $z_{\text{end}} > 6$.

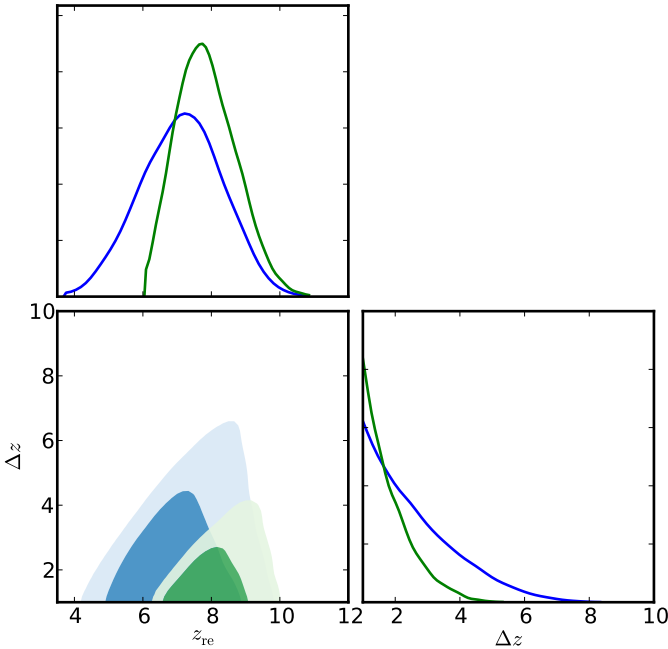


Fig. 14. Posterior distributions on the duration Δz and the redshift z_{re} of reionization from the combination of CMB polarization and kSZ effect constraints using the redshift-symmetric parameterization without (blue) and with (green) the prior $z_{\text{end}} > 6$.

As discussed in Sect. 4.2, the measurement of the total kSZ power constrains the amplitude of patchy reionization, resulting in an upper limit of

$$\Delta z < 4.8 \quad (95\% \text{ CL, uniform prior}), \quad (20)$$

$$\Delta z < 2.8 \quad (95\% \text{ CL, prior } z_{\text{end}} > 6). \quad (21)$$

This is compatible with the constraints from George et al. (2015), where an upper limit was quoted of $z_{20\%} - z_{99\%} < 5.4$ at 95 % CL. Our 95 % CL upper limits on this same quantity are 4.3 and 2.5 without and with the prior on z_{end} , respectively.

For the reionization redshift, we find

$$z_{\text{re}} = 7.2^{+1.2}_{-1.2} \quad (\text{uniform prior}), \quad (22)$$

$$z_{\text{re}} = 7.8^{+1.0}_{-0.8} \quad (\text{prior } z_{\text{end}} > 6), \quad (23)$$

which is compatible within 1σ with the results from CMB *Planck* data alone without the kSZ constraint (Sect. 5.1).

The distributions of z_{end} and z_{beg} are plotted in Fig. 15. Within the redshift-symmetric parameterization, we obtain $z_{\text{beg}} = 8.1^{+1.1}_{-0.9}$ (with the prior on z_{end}).

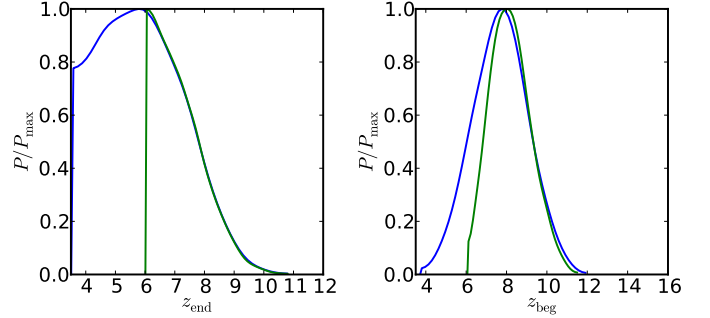


Fig. 15. Posterior distributions of z_{end} and z_{beg} using the redshift-symmetric parameterization, combining *Planck* and VHL data, and using information from the kSZ amplitude, without (blue) and with (green) the prior $z_{\text{end}} > 6$.

Adding information from the kSZ amplitude allows for somewhat tighter constraints to be placed on the reionization duration Δz and the beginning of reionization (corresponding to the 10 % ionization limit) z_{beg} . However, as discussed in Sect. 4.2, those results are very sensitive to details of the simulations used to predict both the shape and the parameter dependences of the kSZ template in the different reionization scenarios (patchy or homogeneous).

6. Discussion

The CMB has long held the promise of measuring the Thomson optical depth in order to derive constraints on the reionization history of the Universe. Despite its importance, this constraint is fundamentally limited by cosmic variance in polarization and is further challenged by foregrounds and systematic effects. The first results, from WMAP, gave $\tau = 0.17 \pm 0.04$, suggesting a reionization redshift between 11 and 30 (Kogut et al. 2003). This was revised in the final 9-year WMAP results to a central value of $\tau = 0.084$ (Hinshaw et al. 2013), which, in the instantaneous reionization model, implies $z_{\text{re}} = 10.4$. However, with the context of the same model, the *Planck* 2015 results (Planck Collaboration XIII 2016), either alone ($z_{\text{re}} = 9.9^{+1.8}_{-1.6}$) or in combination with other data sets ($z_{\text{re}} = 8.8^{+1.3}_{-1.2}$), showed that the reionization redshift was smaller. The main result we present here, $z_{\text{re}} = 8.2^{+1.0}_{-1.2}$, further confirms that reionization occurred rather late, leaving little room for any significant ionization at $z \gtrsim 15$. This is consistent with what is suggested by other reionization probes, which we now discuss (for reviews, see e.g., Becker et al. 2015; McQuinn 2015).

The transition from neutral to ionized gas is constrained by absorption spectra of very distant quasars and gamma ray bursts (GRBs), revealing neutral hydrogen in intergalactic clouds. They show, through the Gunn-Peterson effect, that the diffuse gas in the Universe is mostly ionized up to a redshift of about 6 (Fan et al. 2006a). Given the decline in their abundance beyond redshift $z \simeq 6$, quasars and other active galactic nuclei (AGN) cannot be major contributors to the early stages of reionization (e.g., Willott et al. 2010; Fontanot et al. 2012,

but see Madau & Haardt 2015; Khaire et al. 2016, for alternative AGN-only models). A faint AGN population can produce significant photoionization rates at redshifts of 4–6.5, consistent with the observed highly ionized IGM in the Ly- α forest of high- z quasar spectra (Giallongo et al. 2015). Star-forming galaxies at redshifts $z \gtrsim 6$ have therefore been postulated to be the most likely sources of early reionization, and their time-dependent abundance and spectral properties are crucial ingredients for understanding how intergalactic hydrogen ceased to be neutral (for reviews, see Barkana & Loeb 2001; Fan et al. 2006a; Robertson et al. 2010; McQuinn 2015). The luminosity function of early star-forming galaxies, in particular in the UV domain, is thus an additional and powerful probe of the reionization history (e.g., Kuhlen & Faucher-Giguère 2012; Robertson et al. 2013, 2015; Bouwens et al. 2015). Based on comparison of the 9-year WMAP results to optical depth values inferred from the UV luminosity function of high- z galaxies, it has been suggested that either the UV luminosity density flattens, or physical parameters such as the escape fraction and the clumping factor evolved significantly, or alternatively, additional, undetected sources (such as X-ray binaries and faint AGN) must have existed at $z \gtrsim 11$ (e.g., Kuhlen & Faucher-Giguère 2012; Ellis et al. 2013; Cai et al. 2014; Ishigaki et al. 2015).

The *Planck* results, both from the 2015 data release and those presented here, strongly reduce the need for a significant contribution of Lyman continuum emission at early times. Indeed, as shown in Fig. 16, the present CMB results on the Thomson optical depth, $\tau = 0.058 \pm 0.012$, are perfectly consistent with the best models of star-formation rate densities derived from the UV and IR luminosity functions, as directly estimated from observations of high-redshift galaxies (Ishigaki et al. 2015; Robertson et al. 2015; Bouwens et al. 2015). With the present value of τ , if we maintain a UV-luminosity density at the maximum level allowed by the luminosity density constraints at redshifts $z < 9$, then the currently observed galaxy population at $M_{\text{UV}} < -17$ seems to be sufficient to comply with all the observational constraints without the need for high-redshift ($z = 10$ –15) galaxies.

The *Planck* data are certainly consistent with a fully reionized Universe at $z \approx 6$. Moreover, they seem to be in good agreement with recent observational constraints on reionization in the direction of particular objects. The H I absorption along the line of sight to a distant γ -ray burst, GRB-140515A (Chornock et al. 2014), suggests a Universe containing about a 10 % fraction of neutral hydrogen at $z = 6$ –6.3. At even higher redshifts $z \approx 7$, observation of Ly- α emitters suggests that at least 70 % of the IGM is neutral (Tilvi et al. 2014; Schenker et al. 2014; Faisst et al. 2014). Similarly, quasar near-zone detection and analysis (including sizes, and Ly- α and β transmission properties) have been used to place constraints on z_{end} from signatures of the ionization state of the IGM around individual sources (Wyithe & Loeb 2004; Mesinger & Haiman 2004; Wyithe et al. 2005; Mesinger & Haiman 2007; Carilli et al. 2010; Mortlock et al. 2011; Schroeder et al. 2013). However, interpretation of the observed evolution of the near-zone sizes may be complicated by the opacity caused by absorption systems within the ionized IGM (e.g., Bolton et al. 2011; Bolton & Haehnelt 2013; Becker et al. 2015). Similarly, it is difficult to completely exclude the possibility that damped Ly- α systems contribute to the damping wings of quasar spectra blueward of the Ly- α line (e.g., Mesinger & Furlanetto 2008; Schroeder et al. 2013). Nevertheless, most such studies, indicate that the IGM is significantly neutral at redshifts between 6 and

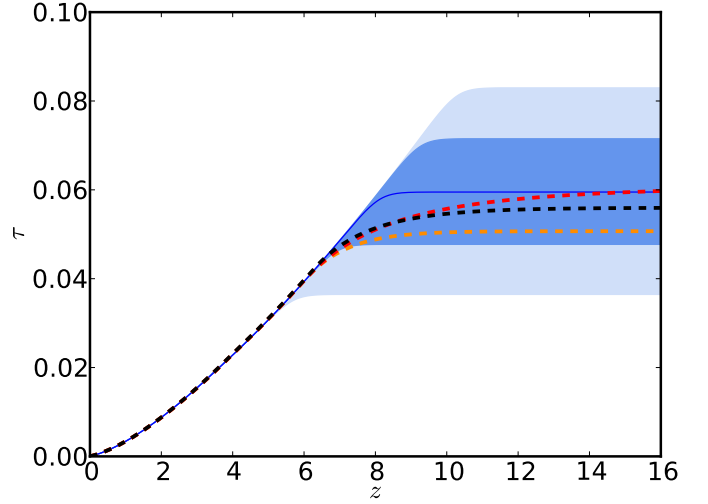


Fig. 16. Evolution of the integrated optical depth for the tanh functional form (with $\delta z = 0.5$, blue shaded area). The two envelopes mark the 68 % and 95 % confidence intervals. The red, black, and orange dashed lines are the models from Bouwens et al. (2015), Robertson et al. (2015), and Ishigaki et al. (2015), respectively, using high-redshift galaxy UV and IR fluxes and/or direct measurements.

7 (see also Keating et al. 2015), in agreement with the current *Planck* results, as shown in Fig. 17.

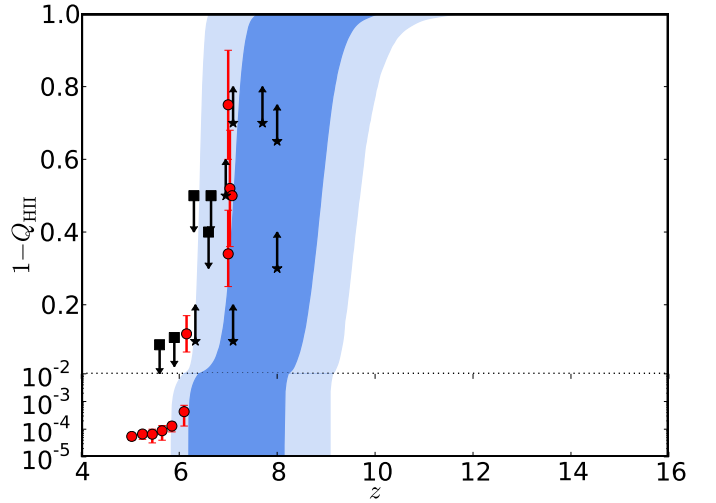


Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints coming from quasars, Ly- α emitters, and the Ly- α forest (compiled by Bouwens et al. 2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the 68 % and 95 % allowed intervals, respectively.

Although there are already all the constraints described above, understanding the formation of the first luminous sources in the Universe is still very much a work in progress. Our new (and lower) value of the optical depth leads to better agreement between the CMB and other astrophysical probes of reionization; however, the fundamental questions remain regarding how reionization actually proceeded.

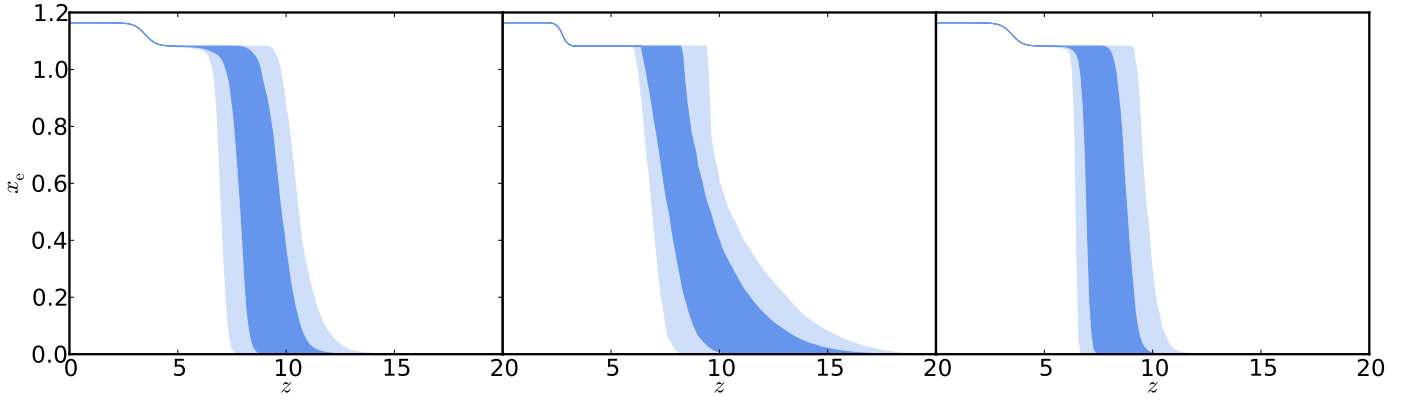


Fig. 18. Constraints on ionization fraction during reionization. The allowed models, in terms of z_{re} and Δz , translate into an allowed region in $x_e(z)$ (68 % and 95 % in dark blue and light blue, respectively), including the $z_{\text{end}} > 6$ prior here. *Left:* Constraints from CMB data using a redshift-symmetric function ($x_e(z)$ as a hyperbolic tangent with $\delta z = 0.5$). *Centre:* Constraints from CMB data using a redshift-asymmetric parameterization ($x_e(z)$ as a power law). *Right:* Constraints from CMB data using a redshift-symmetric parameterization with additional constraints from the kSZ effect.

7. Conclusions

We have derived constraints on cosmic reionization using *Planck* data. The CMB *Planck* power spectra, combining the *EE* polarization at low- ℓ with the temperature data, give, for a so-called “instantaneous” reionization history (a redshift-symmetric tanh function $x_e(z)$ with $\delta z = 0.5$), a measurement of the Thomson optical depth

$$\tau = 0.058 \pm 0.012 \quad (\text{lollipop+PlanckTT}), \quad (24)$$

which is significantly more accurate than previous measurements. Thanks to the relatively high signal-to-noise ratio of the low- ℓ polarization signal, the combination with lensing or data from high-resolution CMB anisotropy experiments (ACT and SPT) does not bring much additional constraining power. The impact on other Λ CDM parameters is only significant for the amplitude of the initial scalar power spectrum A_s and (to a lesser extent) on its tilt n_s . Other parameters are very stable compared to the *Planck* 2015 results.

Using *Planck* data, we have derived constraints on two models for the reionization history $x_e(z)$ that are commonly used in the literature: a redshift-symmetric form using a hyperbolic tangent transition function; and a redshift-asymmetric form parameterized by a power law. We have also investigated the effect of imposing the condition that the reionization is completed by $z = 6$.

Allowing the ionization fraction shape and duration to vary, we have found very compatible best-fit estimates for the optical depth (0.059 and 0.060 for the symmetric and asymmetric model, respectively), showing that the CMB is indeed more sensitive to the value of the optical depth than to the exact shape of the reionization history. However, the value of the reionization redshift does slightly depend on the model considered. In the case of a symmetric parameterization, we have found slightly larger estimates of z_{re} than in the case of instantaneous reionization. This can be understood through the shape of the degeneracy surface between the reionization parameters. For an asymmetric parameterization, z_{re} is smaller, due to the fact that $x_e(z)$ changes more rapidly at the end of reionization than the beginning. We specifically find:

$$z_{\text{re}} = 8.8 \pm 0.9 \quad (\text{redshift-symmetric}), \quad (25)$$

$$z_{\text{re}} = 8.5 \pm 0.9 \quad (\text{redshift-asymmetric}). \quad (26)$$

Assuming two different parameterizations of the reionization history shows how much results on effective parameters (like the redshift of reionization or its duration) are sensitive to the assumption of the reionization history shape. The best models of symmetric and asymmetric parameterization give similar values for τ , and provide reionization redshifts which differ by less than 0.4σ . Constraints on the limits of possible early reionization are similar, leading to 10 % reionization levels at around $z = 10$.

To derive constraints on the duration of the reionization epoch, we combined CMB data with measurements of the amplitude of the kSZ effect. In the case of a redshift-symmetric model, we found

$$\Delta z < 2.8 \quad (95\% \text{ CL}), \quad (27)$$

using the additional constraint that the Universe is entirely reionized at redshift 6 (i.e., $z_{\text{end}} > 6$).

Our final constraints on the reionization history are summarized on Table 1 and plotted in Fig. 18 for each of the aforementioned cases, i.e., the redshift-symmetric and redshift-asymmetric models, using only the CMB, and the redshift-symmetric case using CMB+kSZ (all with prior $z_{\text{end}} > 6$). Plotted this way, the constraints are not very tight and are still fairly model dependent. Given the low value of τ as measured now by *Planck*, the CMB is not able to give tight constraints on details of the reionization history. However, the *Planck* data suggest that an early onset of reionization is disfavoured. In particular, in all cases, we found that the Universe was less than 10 % ionized for redshift $z > 10$. Furthermore, comparisons with other tracers of the ionization history show that our new result on the optical depth eliminates most of the tension between CMB-

Table 1. Constraints on reionization parameters for the different models presented in this paper when including the $z_{\text{end}} > 6$ prior. We show 68% limit for z_{re} and z_{beg} , while we quote 95% upper limit for Δz and z_{end} .

model	z_{re}	Δz	z_{end}	z_{beg}
redshift-symmetric . .	8.8 ± 0.9	< 4.6	< 8.6	9.4 ± 1.2
redshift-asymmetric . .	8.5 ± 0.9	< 6.8	< 8.9	10.4 ± 1.8
redshift-symmetrical with kSZ	7.8 ± 0.9	< 2.8	< 8.8	8.1 ± 1.0

based analyses and constraints from other astrophysical data. Additional sources of reionization, non-standard early galaxies, or significantly evolving escape fractions or clumping factors, are thus not needed.

Ongoing and future experiments like LOFAR, MWA, and SKA, aimed at measuring the redshifted 21-cm signal from neutral hydrogen during the EoR, should be able to probe reionization directly and measure its redshift and duration to high accuracy. Moreover, since reionization appears to happen at redshifts below 10, experiments measuring the global emission of the 21-m line over the sky (e.g., EDGES, Bowman & Rogers 2010, LEDA, Greenhill & Bernardi 2012, DARE, Burns et al. 2012), NenuFAR, Zarka et al. 2012, SARAS, Patra et al. 2013, SCI-HI, Voytek et al. 2014, ZEBRA, Mahesh et al. 2014, and BIGHORNS, Sokolowski et al. 2015) will also be able to derive very competitive constraints on the models (e.g., Liu et al. 2015; Fialkov & Loeb 2016).

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References

- Aghanim, N., Desert, F. X., Puget, J. L., & Gispert, R., Ionization by early quasars and cosmic microwave background anisotropies. 1996, A&A, 311, 1, [arXiv:astro-ph/9604083](#)
- Aghanim, N., Majumdar, S., & Silk, J., Secondary anisotropies of the CMB. 2008, Reports on Progress in Physics, 71, 066902, [arXiv:0711.0518](#)
- Ahn, K., Iliev, I. T., Shapiro, P. R., et al., Detecting the Rise and Fall of the First Stars by Their Impact on Cosmic Reionization. 2012, ApJ, 756, L16, [arXiv:1206.5007](#)
- Barkana, R. & Loeb, A., In the beginning: the first sources of light and the reionization of the universe. 2001, Phys. Rep., 349, 125, [arXiv:astro-ph/0010468](#)
- Battaglia, N., Natarajan, A., Trac, H., Cen, R., & Loeb, A., Reionization on Large Scales. III. Predictions for Low- l Cosmic Microwave Background Polarization and High- l Kinetic Sunyaev-Zel'dovich Observables. 2013, ApJ, 776, 83, [arXiv:1211.2832](#)
- Becker, G. D., Bolton, J. S., Haehnelt, M. G., & Sargent, W. L. W., Detection of extended He II reionization in the temperature evolution of the intergalactic medium. 2011, MNRAS, 410, 1096, [arXiv:1008.2622](#)
- Becker, G. D., Bolton, J. S., & Lidz, A., Reionisation and High-Redshift Galaxies: The View from Quasar Absorption Lines. 2015, PASA, 32, e045, [arXiv:1510.03368](#)
- Becker, R. H., Fan, X., White, R. L., et al., Evidence for Reionization at $z \sim 6$: Detection of a Gunn-Peterson Trough in a $z=6.28$ Quasar. 2001, AJ, 122, 2850, [arXiv:astro-ph/0108097](#)
- Bolton, J. S. & Haehnelt, M. G., On the rapid demise of Ly α emitters at redshift $z \gtrsim 7$ due to the increasing incidence of optically thick absorption systems. 2013, MNRAS, 429, 1695, [arXiv:1208.4417](#)
- Bolton, J. S., Haehnelt, M. G., Warren, S. J., et al., How neutral is the intergalactic medium surrounding the redshift $z = 7.085$ quasar ULAS J1120+0641? 2011, MNRAS, 416, L70, [arXiv:1106.6089](#)
- Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al., Cosmic Reionization after Planck: The Derived Growth of the Ionizing Background now matches the Growth of the Galaxy UV Luminosity Density. 2015, ArXiv:1503.08228, [arXiv:1503.08228](#)
- Bowman, J. D. & Rogers, A. E. E., A lower limit of $\Delta z > 0.06$ for the duration of the reionization epoch. 2010, Nature, 468, 796
- Burns, J. O., Lazio, J., Bale, S., et al., Probing the first stars and black holes in the early Universe with the Dark Ages Radio Explorer (DARE). 2012, Advances in Space Research, 49, 433, [arXiv:1106.5194](#)
- Cai, Z.-Y., Lapi, A., Bressan, A., et al., A Physical Model for the Evolving Ultraviolet Luminosity Function of High Redshift Galaxies and their Contribution to the Cosmic Reionization. 2014, ApJ, 785, 65, [arXiv:1403.0055](#)
- Calabrese, E., Hlozek, R. A., Battaglia, N., et al., Cosmological parameters from pre-planck cosmic microwave background measurements. 2013, Phys. Rev. D, 87, 103012, [arXiv:1302.1841](#)
- Carilli, C. L., Wang, R., Fan, X., et al., Ionization Near Zones Associated with Quasars at $z \sim 6$. 2010, ApJ, 714, 834, [arXiv:1003.0016](#)
- Cen, R., The Universe Was Reionized Twice. 2003, ApJ, 591, 12, [arXiv:astro-ph/0210473](#)
- Chornock, R., Berger, E., Fox, D. B., et al., GRB 140515A at $z=6.33$: Constraints on the End of Reionization From a Gamma-ray Burst in a Low Hydrogen Column Density Environment. 2014, ArXiv e-prints, [arXiv:1405.7400](#)
- Ciardi, B., Ferrara, A., & White, S. D. M., Early reionization by the first galaxies. 2003, MNRAS, 344, L7, [arXiv:astro-ph/0302451](#)
- Colombo, L. P. L. & Pierpaoli, E., Model independent approaches to reionization in the analysis of upcoming CMB data. 2009, New A, 14, 269, [arXiv:0804.0278](#)
- Couchman, H. M. P. & Rees, M. J., Pregalactic evolution in cosmologies with cold dark matter. 1986, MNRAS, 221, 53
- Das, S., Louis, T., Nolta, M. R., et al., The Atacama Cosmology Telescope: temperature and gravitational lensing power spectrum measurements from three seasons of data. 2014, J. Cosmology Astropart. Phys., 4, 14, [arXiv:1301.1037](#)
- Douspis, M., Aghanim, N., Ilić, S., & Langer, M., A new parameterization of the reionisation history. 2015, A&A, 580, L4, [arXiv:1509.02785](#)
- Dunkley, J., Komatsu, E., Nolta, M. R., et al., Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Likelihoods and Parameters from the WMAP data. 2009, ApJS, 180, 306, [arXiv:0803.0586](#)
- Ellis, R. S., McLure, R. J., Dunlop, J. S., et al., The Abundance of Star-forming Galaxies in the Redshift Range 8.5-12: New Results from the 2012 Hubble Ultra Deep Field Campaign. 2013, ApJ, 763, L7, [arXiv:1211.6804](#)
- Faisst, A. L., Capak, P., Carollo, C. M., Scarlata, C., & Scoville, N., Spectroscopic Observation of Ly α Emitters at $z \sim 7.7$ and Implications on Re-ionization. 2014, ApJ, 788, 87
- Fan, X., Strauss, M. A., Becker, R. H., et al., Constraining the Evolution of the Ionizing Background and the Epoch of Reionization with $z \sim 6$ Quasars. II. A Sample of 19 Quasars. 2006a, AJ, 132, 117, [arXiv:astro-ph/0512082](#)
- Fan, X., Strauss, M. A., Richards, G. T., et al., A Survey of $z > 5.7$ Quasars in the Sloan Digital Sky Survey. IV. Discovery of Seven Additional Quasars. 2006b, AJ, 131, 1203, [arXiv:astro-ph/0512080](#)
- Fialkov, A. & Loeb, A., Precise Measurement of the Reionization Optical Depth from The Global 21-cm Signal Accounting for Cosmic Heating. 2016, ArXiv e-prints, [arXiv:1601.03058](#)
- Fontanot, F., Cristiani, S., & Vanzella, E., On the relative contribution of high-redshift galaxies and active galactic nuclei to reionization. 2012, MNRAS, 425, 1413, [arXiv:1206.5810](#)
- Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L., The Growth of H II Regions During Reionization. 2004, ApJ, 613, 1, [arXiv:astro-ph/0403697](#)
- George, E. M., Reichardt, C. L., Aird, K. A., et al., A Measurement of Secondary Cosmic Microwave Background Anisotropies from the 2500 Square-degree SPT-SZ Survey. 2015, ApJ, 799, 177, [arXiv:1408.3161](#)
- Giallongo, E., Grazian, A., Fiore, F., et al., Faint AGNs at $z \gtrsim 4$ in the CANDELS GOODS-S field: looking for contributors to the reionization of the Universe. 2015, A&A, 578, A83, [arXiv:1502.02562](#)
- Gnedin, N. Y., Cosmological Reionization by Stellar Sources. 2000, ApJ, 535, 530, [arXiv:astro-ph/9909383](#)
- Greenhill, L. J. & Bernardi, G., HI Epoch of Reionization Arrays. 2012, ArXiv e-prints, [arXiv:1201.1700](#)
- Gruzinov, A. & Hu, W., Secondary Cosmic Microwave Background Anisotropies in a Universe Reionized in Patches. 1998, ApJ, 508, 435, [arXiv:astro-ph/9803188](#)
- Gunn, J. E. & Peterson, B. A., On the Density of Neutral Hydrogen in Intergalactic Space. 1965, ApJ, 142, 1633
- Hamimeche, S. & Lewis, A., Likelihood analysis of CMB temperature and polarization power spectra. 2008, Phys. Rev. D, 77, 103013, [arXiv:0801.0554](#)
- Hasselfield, M., Moodley, K., Bond, J. R., et al., The Atacama Cosmology Telescope: Beam Measurements and the Microwave Brightness Temperatures of Uranus and Saturn. 2013, ApJS, 209, 17, [arXiv:1303.4714](#)
- Hinshaw, G., Larson, D., Komatsu, E., et al., Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results. 2013, ApJS, 208, 19, [arXiv:1212.5226](#)
- Holder, G. P., Haيمان, Z., Kaplinghat, M., & Knox, L., The Reionization History at High Redshifts. II. Estimating the Optical Depth to Thomson Scattering from Cosmic Microwave Background Polarization. 2003, ApJ, 595, 13, [arXiv:astro-ph/0302404](#)
- Hu, W. & Holder, G. P., Model-independent reionization observables in the CMB. 2003, Phys. Rev. D, 68, 023001
- Iliev, I. T., Mellema, G., Ahn, K., et al., Simulating cosmic reionization: how large a volume is large enough? 2014, MNRAS, 439, 725, [arXiv:1310.7463](#)
- Ishigaki, M., Kawamata, R., Ouchi, M., et al., Hubble Frontier Fields First Complete Cluster Data: Faint Galaxies at $z \sim 5-10$ for UV Luminosity

- Functions and Cosmic Reionization. 2015, *ApJ*, 799, 12, [arXiv:1408.6903](#)
- Keating, L. C., Haehnelt, M. G., Cantalupo, S., & Puchwein, E., Probing the end of reionization with the near zones of $z \gtrsim 6$ QSOs. 2015, *MNRAS*, 454, 681, [arXiv:1506.03396](#)
- Khair, V., Srianand, R., Choudhury, T. R., & Gaikwad, P., The redshift evolution of escape fraction of hydrogen ionizing photons from galaxies. 2016, *MNRAS*, 457, 4051, [arXiv:1510.04700](#)
- Kogut, A., Spergel, D. N., Barnes, C., et al., First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature-Polarization Correlation. 2003, *ApJS*, 148, 161, [arXiv:astro-ph/0302213](#)
- Komatsu, E., Smith, K. M., Dunkley, J., et al., Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation. 2011, *ApJS*, 192, 18, [arXiv:1001.4538](#)
- Kuhlen, M. & Faucher-Giguère, C.-A., Concordance models of reionization: implications for faint galaxies and escape fraction evolution. 2012, *MNRAS*, 423, 862, [arXiv:1201.0757](#)
- Lesgourgues, J., The Cosmic Linear Anisotropy Solving System (CLASS) I: Overview. 2011, ArXiv e-prints, [arXiv:1104.2932](#)
- Lewis, A., Cosmological parameters from WMAP 5-year temperature maps. 2008, *Phys. Rev. D*, 78, 023002, [arXiv:0804.3865](#)
- Lewis, A., Weller, J., & Battye, R., The cosmic microwave background and the ionization history of the Universe. 2006, *MNRAS*, 373, 561, [arXiv:astro-ph/0606552](#)
- Liu, A., Pritchard, J. R., Allison, R., et al., Eliminating the optical depth nuisance from the CMB with 21 cm cosmology. 2015, ArXiv e-prints, [arXiv:1509.08463](#)
- Madau, P. & Haardt, F., Cosmic Reionization after Planck: Could Quasars Do It All? 2015, *ApJ*, 813, L8, [arXiv:1507.07678](#)
- Madau, P., Haardt, F., & Rees, M. J., Radiative Transfer in a Clumpy Universe. III. The Nature of Cosmological Ionizing Sources. 1999, *ApJ*, 514, 648, [arXiv:astro-ph/9809058](#)
- Mahesh, N., Subrahmanyan, R., Udaya Shankar, N., & Raghunathan, A., A Resistive Wideband Space Beam Splitter. 2014, ArXiv e-prints, [arXiv:1406.2585](#)
- Mangilli, A., Plaszczynski, S., & Tristram, M., Large-scale CMB temperature and polarization cross-spectra likelihoods. 2015, *MNRAS* submitted, [arXiv:1503.01347](#)
- McQuinn, M., The Evolution of the Intergalactic Medium. 2015, ArXiv e-prints, [arXiv:1512.00086](#)
- McQuinn, M., Furlanetto, S. R., Hernquist, L., Zahn, O., & Zaldarriaga, M., The Kinetic Sunyaev-Zel'dovich Effect from Reionization. 2005, *ApJ*, 630, 643, [arXiv:astro-ph/0504189](#)
- Meiksin, A. & Madau, P., On the photoionization of the intergalactic medium by quasars at high redshift. 1993, *ApJ*, 412, 34
- Mesinger, A., ed. 2016, *Astrophysics and Space Science Library*, Vol. 423, Understanding the Epoch of Cosmic Reionization (Springer International Publishing)
- Mesinger, A. & Furlanetto, S. R., $\text{Ly}\alpha$ damping wing constraints on inhomogeneous reionization. 2008, *MNRAS*, 385, 1348, [arXiv:0710.0371](#)
- Mesinger, A. & Haiman, Z., Evidence of a Cosmological Strömgren Surface and of Significant Neutral Hydrogen Surrounding the Quasar SDSS J1030+0524. 2004, *ApJ*, 611, L69, [arXiv:astro-ph/0406188](#)
- Mesinger, A. & Haiman, Z., Constraints on Reionization and Source Properties from the Absorption Spectra of $z > 6.2$ Quasars. 2007, *ApJ*, 660, 923, [arXiv:astro-ph/0610258](#)
- Mesinger, A., McQuinn, M., & Spergel, D. N., The kinetic Sunyaev-Zel'dovich signal from inhomogeneous reionization: a parameter space study. 2012, *MNRAS*, 422, 1403, [arXiv:1112.1820](#)
- Miralda-Escude, J. & Ostriker, J. P., What produces the ionizing background at large redshift? 1990, *ApJ*, 350, 1
- Mitra, S., Choudhury, T. R., & Ferrara, A., Reionization constraints using principal component analysis. 2011, *MNRAS*, 413, 1569, [arXiv:1011.2213](#)
- Mortlock, D. J., Warren, S. J., Venemans, B. P., et al., A luminous quasar at a redshift of $z = 7.085$. 2011, *Nature*, 474, 616, [arXiv:1106.6088](#)
- Mortonson, M. J. & Hu, W., Model-Independent Constraints on Reionization from Large-Scale Cosmic Microwave Background Polarization. 2008, *ApJ*, 672, 737, [arXiv:0705.1132](#)
- Ostriker, J. P. & Vishniac, E. T., Generation of microwave background fluctuations from nonlinear perturbations at the ERA of galaxy formation. 1986, *ApJ*, 306, L51
- Page, L., Hinshaw, G., Komatsu, E., et al., Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis. 2007, *ApJS*, 170, 335, [arXiv:astro-ph/0603450](#)
- Pandolfi, S., Ferrara, A., Choudhury, T. R., Melchiorri, A., & Mitra, S., Data-constrained reionization and its effects on cosmological parameters. 2011, *Phys. Rev. D*, 84, 123522, [arXiv:1111.3570](#)
- Park, H., Shapiro, P. R., Komatsu, E., et al., The Kinetic Sunyaev-Zel'dovich Effect as a Probe of the Physics of Cosmic Reionization: The Effect of Self-regulated Reionization. 2013, *ApJ*, 769, 93, [arXiv:1301.3607](#)
- Patra, N., Subrahmanyan, R., Raghunathan, A., & Udaya Shankar, N., SARAS: a precision system for measurement of the cosmic radio background and signatures from the epoch of reionization. 2013, *Experimental Astronomy*, 36, 319, [arXiv:1211.3800](#)
- Peebles, P. J. E., Recombination of the Primeval Plasma. 1968, *ApJ*, 153, 1
- Planck Collaboration XV, *Planck* 2013 results. XV. CMB power spectra and likelihood. 2014, *A&A*, 571, A15, [arXiv:1303.5075](#)
- Planck Collaboration XVI, *Planck* 2013 results. XVI. Cosmological parameters. 2014, *A&A*, 571, A16, [arXiv:1303.5076](#)
- Planck Collaboration XX, *Planck* 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts. 2014, *A&A*, 571, A20, [arXiv:1303.5080](#)
- Planck Collaboration II, *Planck* 2015 results. II. Low Frequency Instrument data processing. 2016, *A&A*, in press, [arXiv:1502.01583](#)
- Planck Collaboration VII, *Planck* 2015 results. VII. High Frequency Instrument data processing: Time-ordered information and beam processing. 2016, *A&A*, in press, [arXiv:1502.01586](#)
- Planck Collaboration VIII, *Planck* 2015 results. VIII. High Frequency Instrument data processing: Calibration and maps. 2016, *A&A*, in press, [arXiv:1502.01587](#)
- Planck Collaboration IX, *Planck* 2015 results. IX. Diffuse component separation: CMB maps. 2016, *A&A*, in press, [arXiv:1502.01596](#)
- Planck Collaboration X, *Planck* 2015 results. X. Diffuse component separation: Foreground maps. 2016, *A&A*, in press, [arXiv:1502.01588](#)
- Planck Collaboration XI, *Planck* 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters. 2016, *A&A*, in press, [arXiv:1507.02704](#)
- Planck Collaboration XIII, *Planck* 2015 results. XIII. Cosmological parameters. 2016, *A&A*, in press, [arXiv:1502.01589](#)
- Planck Collaboration XV, *Planck* 2015 results. XV. Gravitational lensing. 2016, *A&A*, in press, [arXiv:1502.01591](#)
- Planck Collaboration Int. XLVI, *Planck* intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth. 2016, *A&A*, submitted, [arXiv:1605.02985](#)
- Pritchard, J. R., Loeb, A., & Wyithe, J. S. B., Constraining reionization using 21-cm observations in combination with CMB and $\text{Ly}\alpha$ forest data. 2010, *MNRAS*, 408, 57, [arXiv:0908.3891](#)
- Reichardt, C. L., Shaw, L., Zahn, O., et al., A Measurement of Secondary Cosmic Microwave Background Anisotropies with Two Years of South Pole Telescope Observations. 2012, *ApJ*, 755, 70, [arXiv:1111.0932](#)
- Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., & Stark, D. P., Early star-forming galaxies and the reionization of the Universe. 2010, *Nature*, 468, 49, [arXiv:1011.0727](#)
- Robertson, B. E., Ellis, R. S., Furlanetto, S. R., & Dunlop, J. S., Cosmic Reionization and Early Star-forming Galaxies: A Joint Analysis of New Constraints from Planck and the Hubble Space Telescope. 2015, *ApJ*, 802, L19, [arXiv:1502.02024](#)
- Robertson, B. E., Furlanetto, S. R., Schneider, E., et al., New Constraints on Cosmic Reionization from the 2012 Hubble Ultra Deep Field Campaign. 2013, *ApJ*, 768, 71, [arXiv:1301.1228](#)
- Schenker, M. A., Ellis, R. S., Konidaris, N. P., & Stark, D. P., Line-emitting Galaxies beyond a Redshift of 7: An Improved Method for Estimating the Evolving Neutrality of the Intergalactic Medium. 2014, *ApJ*, 795, 20, [arXiv:1404.4632](#)
- Schroeder, J., Mesinger, A., & Haiman, Z., Evidence of Gunn-Peterson damping wings in high- z quasar spectra: strengthening the case for incomplete reionization at $z \sim 6-7$. 2013, *MNRAS*, 428, 3058, [arXiv:1204.2838](#)
- Seager, S., Sasselov, D. D., & Scott, D., How Exactly Did the Universe Become Neutral? 2000, *ApJS*, 128, 407, [arXiv:astro-ph/9912182](#)
- Shaw, L. D., Rudd, D. H., & Nagai, D., Deconstructing the Kinetic SZ Power Spectrum. 2012, *ApJ*, 756, 15, [arXiv:1109.0553](#)
- Sokolowski, M., Tremblay, S. E., Wayth, R. B., et al., BIGHORNS - Broadband Instrument for Global Hydrogen Reionisation Signal. 2015, *PASA*, 32, e004, [arXiv:1501.02922](#)
- Sunyaev, R. A. & Zeldovich, I. B., The velocity of clusters of galaxies relative to the microwave background - The possibility of its measurement. 1980, *MNRAS*, 190, 413
- Tilvi, V., Papovich, C., Finkelstein, S. L., et al., Rapid Decline of $\text{Ly}\alpha$ Emission toward the Reionization Era. 2014, *ApJ*, 794, 5, [arXiv:1405.4869](#)
- Trac, H., Bode, P., & Ostriker, J. P., Templates for the Sunyaev-Zel'dovich Angular Power Spectrum. 2011, *ApJ*, 727, 94, [arXiv:1006.2828](#)
- Tristram, M., Macías-Pérez, J. F., Renault, C., & Santos, D., XSPECT, estimation of the angular power spectrum by computing cross-power spectra with analytical error bars. 2005, *MNRAS*, 358, 833, [arXiv:astro-ph/0405575](#)
- Venemans, B. P., Findlay, J. R., Sutherland, W. J., et al., Discovery of Three $z > 6.5$ Quasars in the VISTA Kilo-Degree Infrared Galaxy (VIKING) Survey. 2013, *ApJ*, 779, 24, [arXiv:1311.3666](#)
- Voytek, T. C., Natarajan, A., Garca, J. M. J., Peterson, J. B., & Lopez-Cruz, O., Probing the Dark Ages at $z \sim 20$: The SCI-HI 21cm All-sky Spectrum

- Experiment. 2014, *The Astrophysical Journal Letters*, 782, L9
- Willott, C. J., Delorme, P., Rey, C., et al., The Canada-France High-z Quasar Survey: Nine New Quasars and the Luminosity Function at Redshift 6. 2010, *AJ*, 139, 906, [arXiv:0912.0281](#)
- Worseck, G., Prochaska, J. X., Hennawi, J. F., & McQuinn, M., Early and Extended Helium Reionization Over More Than 600 Million Years of Cosmic Time. 2014, *ArXiv e-prints*, [arXiv:1405.7405](#)
- Wyithe, J. S. B. & Loeb, A., A characteristic size of ~ 10 Mpc for the ionized bubbles at the end of cosmic reionization. 2004, *Nature*, 432, 194, [arXiv:astro-ph/0409412](#)
- Wyithe, J. S. B., Loeb, A., & Carilli, C., Improved Constraints on the Neutral Intergalactic Hydrogen surrounding Quasars at Redshifts $z > 6$. 2005, *ApJ*, 628, 575, [arXiv:astro-ph/0411625](#)
- Zahn, O., Reichardt, C. L., Shaw, L., et al., Cosmic Microwave Background Constraints on the Duration and Timing of Reionization from the South Pole Telescope. 2012, *ApJ*, 756, 65, [arXiv:1111.6386](#)
- Zarka, P., Girard, J. N., Tagger, M., & Denis, L. 2012, in *SF2A-2012: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, ed. S. Boissier, P. de Laverny, N. Nardetto, R. Samadi, D. Valls-Gabaud, & H. Wozniak, 687–694
- Zel'dovich, Y. B., Kurt, V. G., & Syunyaev, R. A., Recombination of Hydrogen in the Hot Model of the Universe. 1969, *Soviet Journal of Experimental and Theoretical Physics*, 28, 146

Appendix A: the Lollipop likelihood

lollipop, the LOW- ℓ Likelihood on Polarized Power-spectra, is a likelihood function based on cross-power spectra for the low multipoles. The idea behind this approach is that the noise can be considered as uncorrelated between maps and that systematics will be considerably reduced in cross-correlation compared to auto-correlation.

At low multipoles and for incomplete sky coverage, the C_ℓ s are not Gaussian distributed and are correlated between multipoles. **lollipop** uses the approximation presented in [Hamimeche & Lewis \(2008\)](#), modified as described in [Mangilli et al. \(2015\)](#) to apply to cross-power spectra. The idea is to apply a change of variable $C_\ell \rightarrow X_\ell$ so that the new variable X_ℓ is Gaussian. Similarly to [Hamimeche & Lewis \(2008\)](#), we define

$$X_\ell = \sqrt{C_\ell^f + O_\ell} g\left(\frac{\tilde{C}_\ell + O_\ell}{C_\ell^f + O_\ell}\right) \sqrt{C_\ell^f + O_\ell}, \quad (\text{A.1})$$

where $g(x) = \sqrt{2(x - \ln(x) - 1)}$, \tilde{C}_ℓ are the measured cross-power spectra, C_ℓ are the power-spectra of the model to evaluate, C_ℓ^f is a fiducial model, and O_ℓ are the offsets needed in the case of cross-spectra. For multi-dimensional CMB modes (i.e., T , E , and B), C_ℓ is a 3×3 matrix of power-spectra:

$$C_\ell = \begin{pmatrix} C_\ell^{TT} & C_\ell^{TE} & C_\ell^{TB} \\ C_\ell^{ET} & C_\ell^{EE} & C_\ell^{EB} \\ C_\ell^{BT} & C_\ell^{BE} & C_\ell^{BB} \end{pmatrix}_\ell, \quad (\text{A.2})$$

and the g function is applied to the eigenvalues of $C_\ell^{-1/2} \tilde{C}_\ell C_\ell^{-1/2}$.

In the case of auto-spectra, the offsets are replaced by the noise bias effectively present in the measured power-spectra. For cross-power spectra, the noise bias is null and here we use the effective offsets defined from the C_ℓ noise variance:

$$\Delta C_\ell \equiv \sqrt{\frac{2}{2\ell + 1}} O_\ell. \quad (\text{A.3})$$

The distribution of the new variable X can be approximated as Gaussian, with a covariance given by the covariance of the C_ℓ s. The likelihood function of the C_ℓ given the data \tilde{C}_ℓ is then

$$-2 \ln P(C_\ell | \tilde{C}_\ell) = \sum_{\ell\ell'} X_\ell^T M_{\ell\ell'}^{-1} X_{\ell'}, \quad (\text{A.4})$$

where the C_ℓ covariance matrix $M_{\ell\ell'}$ is estimated via Monte Carlo simulations.

In this paper, we restrict ourselves to the one-field approximation in order to derive a likelihood function based only on the EE power spectrum at very low multipoles. We use a conservative sky fraction including 50 % of the sky, with a Galactic mask based on a threshold on the polarisation amplitude measured in the 353 GHz *Planck* channel, further apodized using a 4° Gaussian taper (see Fig. A.1). We use Xpol (a pseudo- C_ℓ estimator described in [Tristram et al. 2005](#) extended to polarisation) to derive cross-power spectra between the 100 and 143 GHz channel maps from *Planck*. We also reject the first two multipoles ($\ell = 2$ and 3), since they are more subject to contamination by residual instrumental effects (see [Planck Collaboration Int. XLVI 2016](#)).

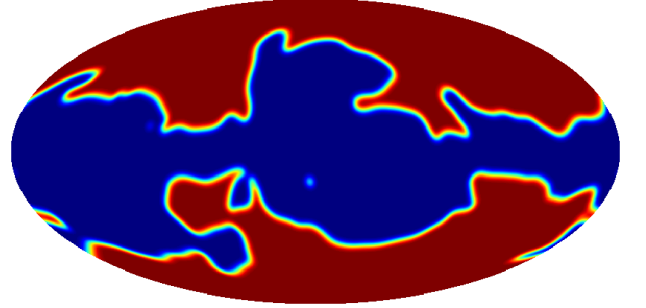


Fig. A.1. Galactic mask used for the lollipop likelihood, covering 50 % of the sky.

This likelihood has been tested on Monte Carlo simulations including signal (CMB and foregrounds), realistic noise, and systematic effects. The simulated maps are then foreground-subtracted, using the same procedure as for the data. We constructed the C_ℓ covariance matrix $M_{\ell\ell'}$ using those simulations. Figure A.2 shows the distribution of the recovered τ values for an input model with $\tau = 0.06$, fixing all other cosmological parameters to the *Planck* 2015 best-fit values (including $A_s e^{-2\tau}$).

To validate the choice of multipole and the stability of the result on τ , we performed several consistency checks on the *Planck* data. Among them, we varied the minimum multipole used (from $\ell = 2$ to $\ell = 4$) and allowed for larger sky coverage (increasing to 60 % of the sky). The results are summarized in Fig. A.3.

Appendix B: Impact on Λ CDM parameters

In addition to the restricted parameter set shown in Fig. 6, we describe here the impact of the lollipop likelihood on Λ CDM parameters in general. Figure B.1 compares results from lollipop+PlanckTT with the lowP+PlanckTT 2015. The new low- ℓ polarization results are sufficiently powerful that they break the degeneracy between n_s and τ . The contours for τ and A_s , where the lollipop likelihood dominates the constraint, are significantly reduced. The impact on other Λ CDM parameters are small, typically below 0.3σ .

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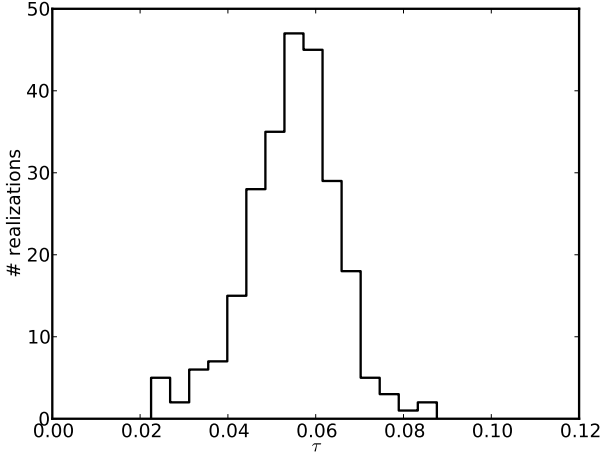


Fig. A.2. Distribution of the peak value of the posterior distribution for optical depth from end-to-end simulations including noise, systematic effects, Galactic dust signal, and CMB with the fiducial value of $\tau = 0.06$.

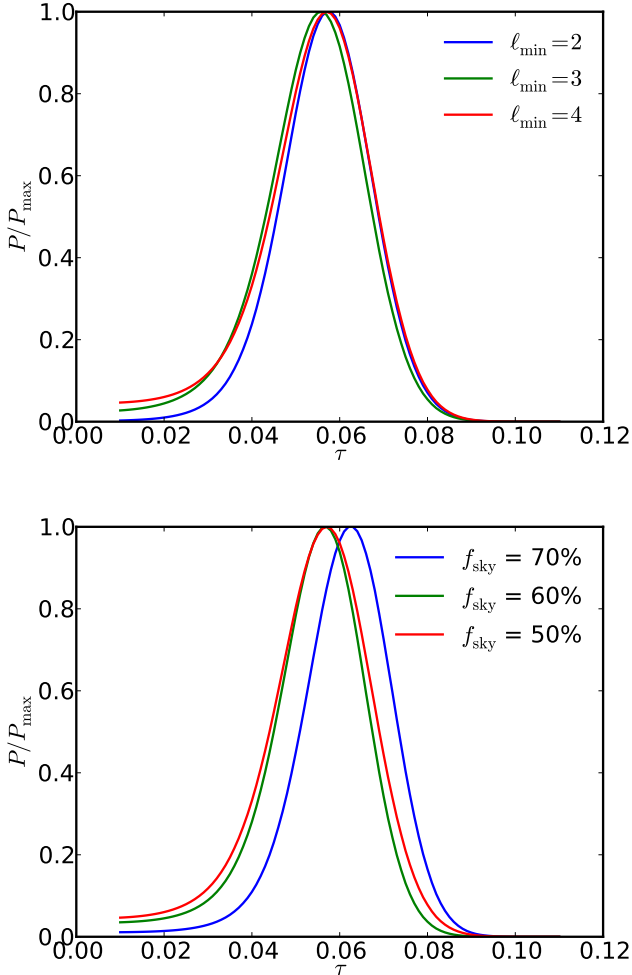


Fig. A.3. Posterior distributions for optical depth, showing the effect of changing two of the choices made in our analysis. *Top:* Different choices of minimum multipole. *Bottom:* Different choices of sky fraction used.

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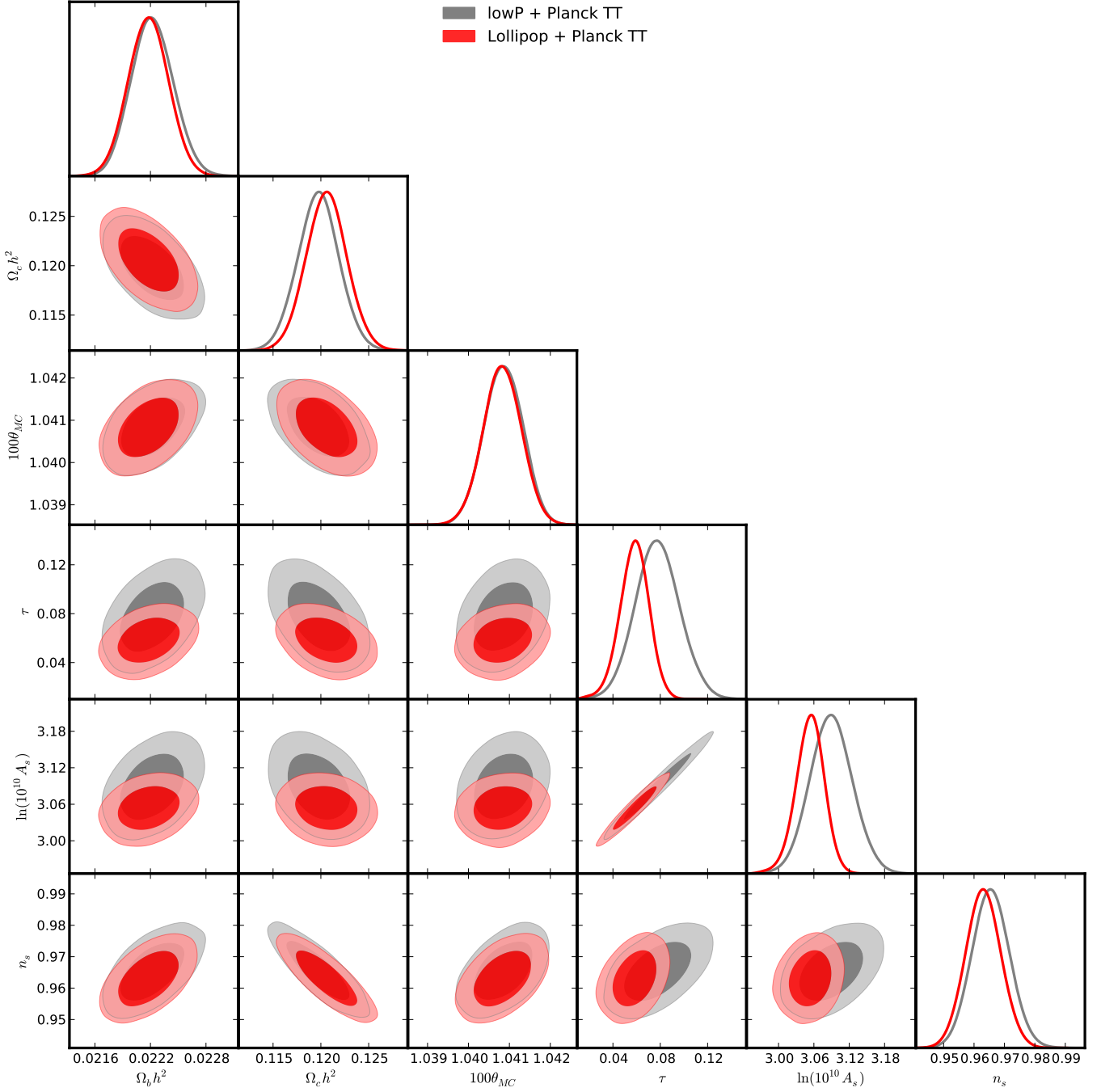


Fig. B.1. Λ CDM parameters for PlanckTT combined with the low- ℓ polarization likelihood from the *Planck* 2015 release (lowP, in grey) and from this work (lollipop, in red).

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